Solid State Ballast Tube Emulator For Vintage Equipment

27-Apr-2021, Rev. 30-Apr-2022 pg.11

Virgil Cheng, vr2xgm

Ballast tube overview:

- A positive temperature coefficient resistor made with a filament housed inside a gas filled envelope for heat transfer
- Abrupt resistance to temperature profile resulting in good constant current limiting characteristic

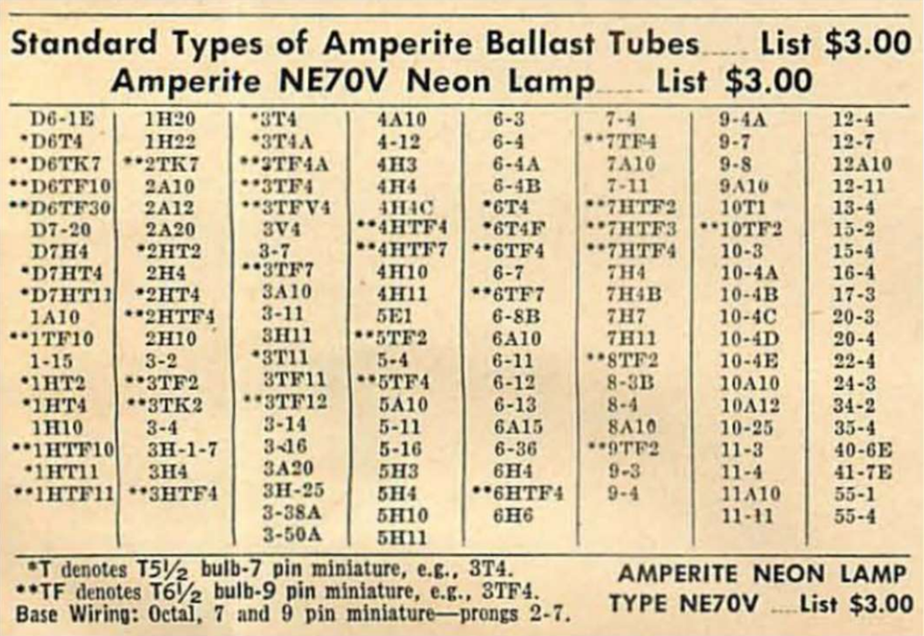
Motivation:

- Limited lifetime, specific part numbers becoming difficult to find
- Most solid-state replacements are DC electronic constant current load with front end bridge rectifier
    - Advantages: simple
    - Disadvantages: does not draw sinusoidal current from filament power, causing current harmonics on filament circuit
- This exercise is to built a closer electrical ballast tube equivalent
    - Resistive behavior, current proportional to voltage, unity power factor
    - Bidirectional, operates on both polarities
    - Similar cross-sectional dimension compared to original glass envelope, acceptable thermal performance
    - Higher density component packaging to compensate increase in component count

Example devices:

Part number	Current (A)	Min voltage (V)	Power (W)	Size	Where used
3TF7	0.3	7	5	T6-1/2 bulb 9 pin miniature 2-1/2”h 7/8”dia	R390A receiver
1HT4	0.1	4	5	T5-1/2 bulb 7 pin miniature 2-1/2”h ¾”dia	AN/FRR-23 receiver
WL8P	0.78-0.92	5.5	10.6	Octal, 95mm h, 33mm dia	222-1 receiver

Amperite parts catalogue, 1960

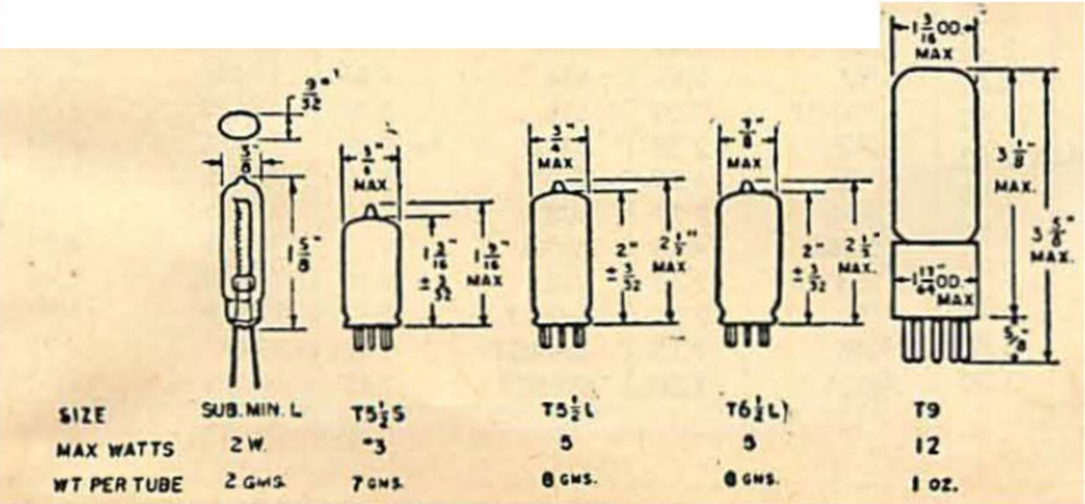


Standard Types of Amperite Ballast Tubes..... List $3.00
Amperite NE70V Neon Lamp..... List $3.00

D6-1E
*D6T4
**D6TK7
**D6TF10
**D6TF30
D7-20
D7H4
*D7HT4
*D7HT11
1A10
**1TF10
1-15
*1HT2
*1HT4
1H10
**1HTF10
*1HT11
**1HTF11
1H20
1H22
**2TK7
2A10
2A12
2A20
*2HT2
2H4
*2HT4
**2HTF4
2H10
3-2
**3TF2
**3TK2
3-4
3H-1-7
3H4
**3HTF4
*3T4
*3T4A
**3TF4A
**3TF4
**3TFV4
3V4
3-7
**3TF7
3A10
3-11
3H11
*3T11
3TF11
**3TF12
3-14
3-16
3A20
3H-25
3-38A
3-50A
4A10
4-12
4H3
4H4
4H4C
**4HTF4
**4HTF7
4H10
4H11
5E1
**5TF2
5-4
**5TF4
5A10
5-11
5-16
5H3
5H4
5H10
5H11
6-3
6-4
6-4A
6-4B
*6T4
*6T4F
**6TF4
6-7
**6TF7
6-8B
6A10
6-11
6-12
6-13
6A15
6-36
6H4
**6HTF4
6H6
7-4
**7TF4
7A10
7-11
**7HTF2
**7HTF3
**7HTF4
7H4
7H4B
7H7
7H11
**8TF2
8-3B
8-4
8A10
**9TF2
9-3
9-4
9-4A
9-7
9-8
9A10
10T1
**10TF2
10-3
10-4A
10-4B
10-4C
10-4D
10-4E
10A10
10A12
10-25
11-3
11-4
11A10
11-11
12-4
12-7
12A10
12-11
13-4
15-2
15-4
16-4
17-3
20-3
20-4
22-4
24-3
34-2
35-4
40-6E
41-7E
55-1
55-4

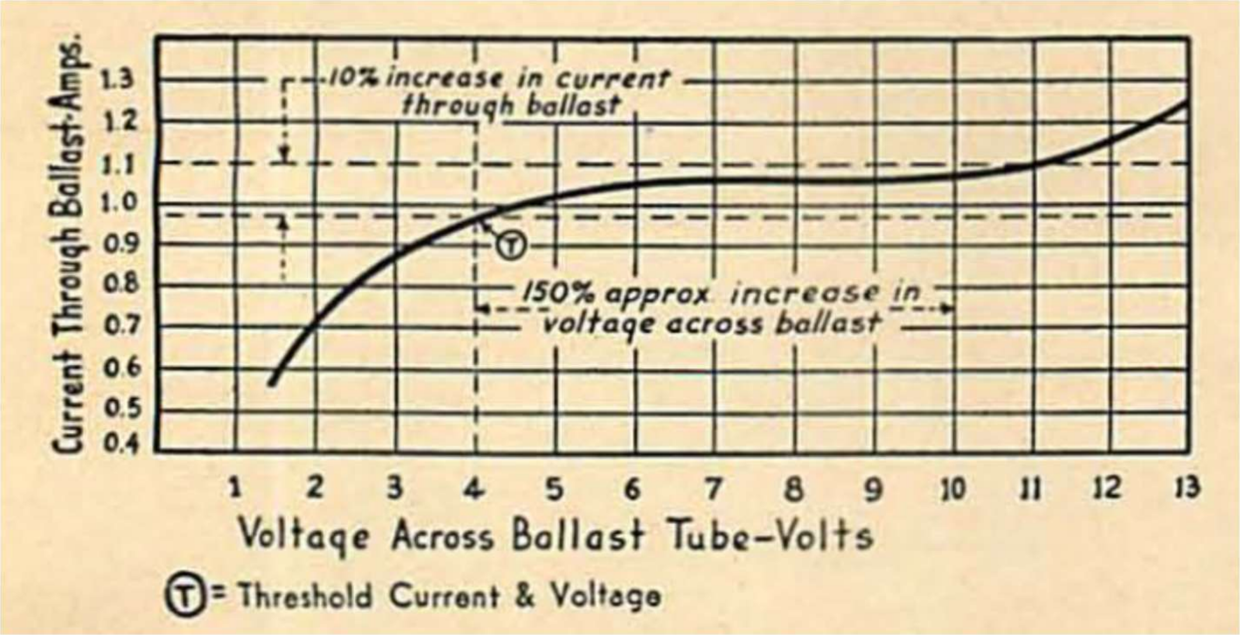
*T denotes T5½ bulb-7 pin miniature, e.g., 3T4.
**TF denotes T6½ bulb-9 pin miniature, e.g., 3TF4.
Base Wiring: Octal, 7 and 9 pin miniature—prongs 2-7.

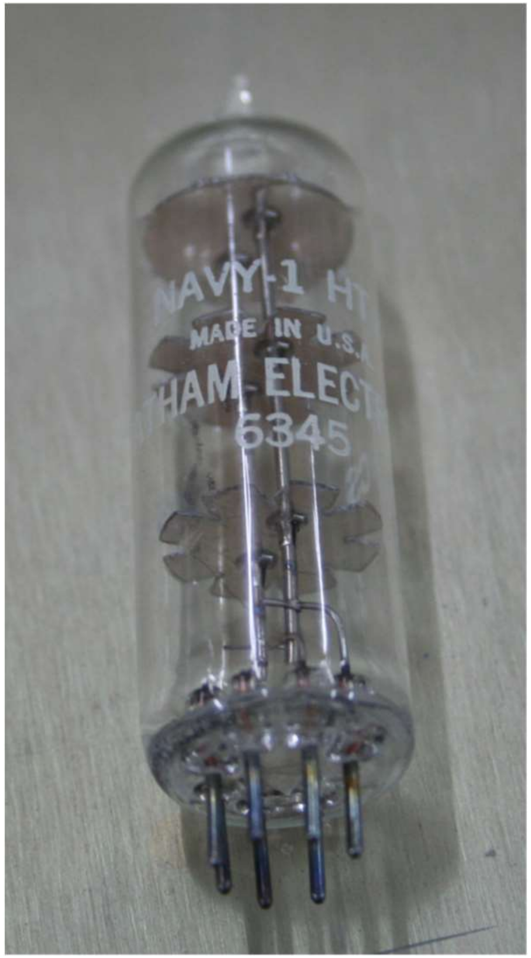
AMPERITE NEON LAMP
TYPE NE70V ....List $3.00



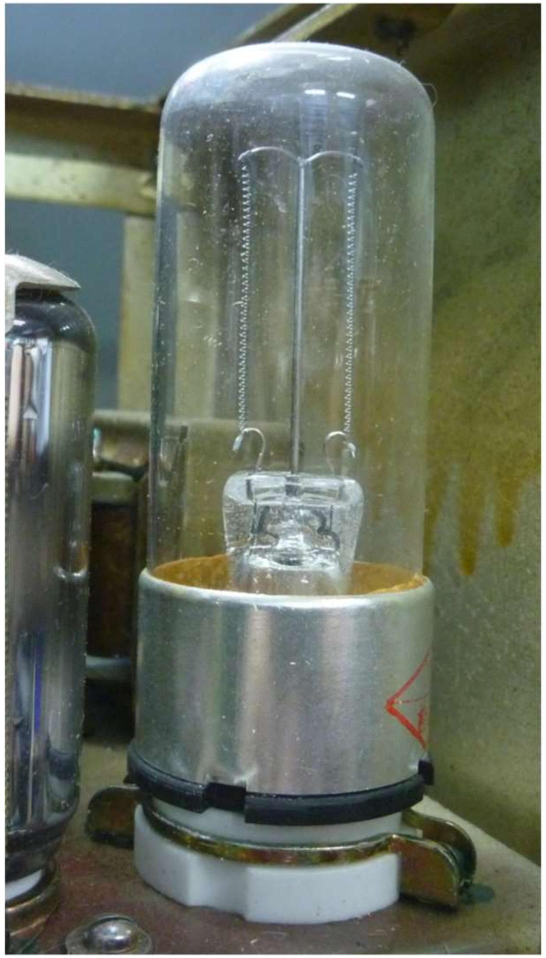
SIZE	SUB. MIN. L	T5½S	T5½L	T6½L)	T9
MAX WATTS	2 W.	*3	5	5	12
WT PER TUBE	2 GMS.	7 GMS.	8 GMS.	8 GMS.	1 OZ.

Example ballast tube Current – Voltage curve, Amperite 1960 datasheet

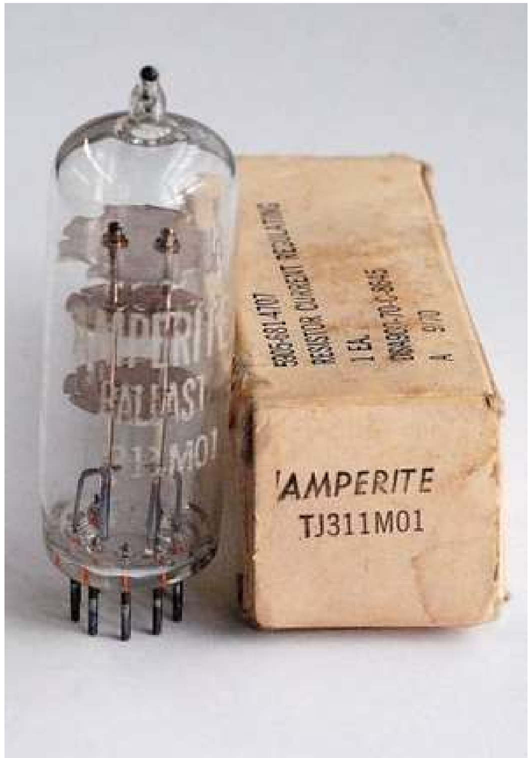




1HT4 used on AN/FRR-23

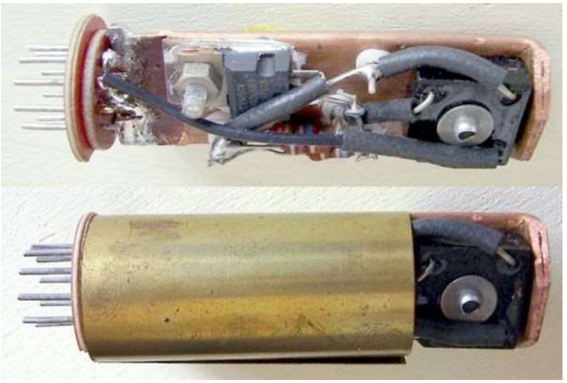


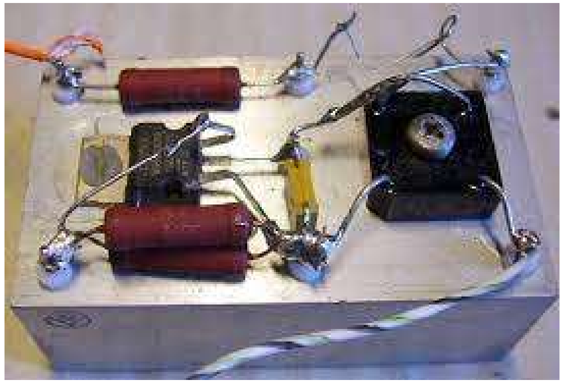
WL8P used on 222-1

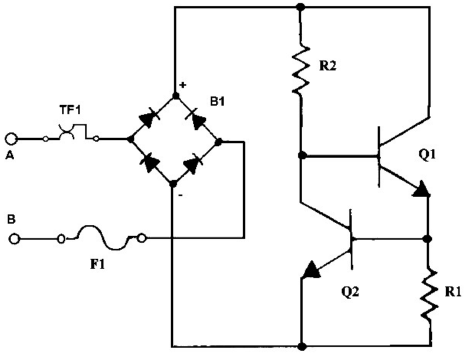


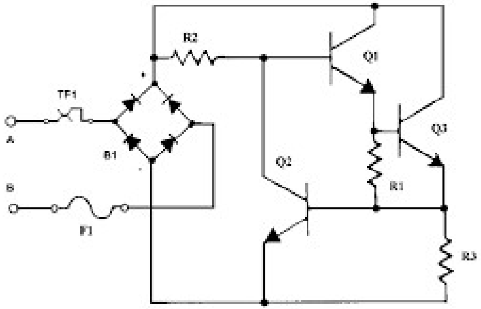
3TF7 used on R390A
www photo

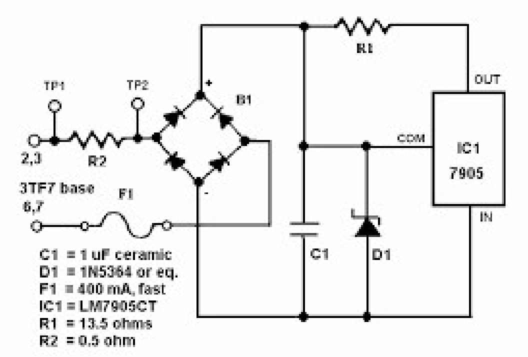
Solid state ballast tube replacement, www examples

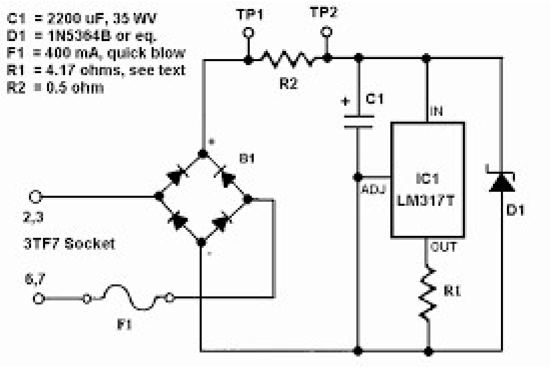


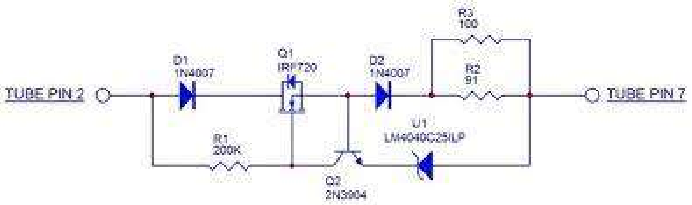












Simple, reliable

Alternatives:

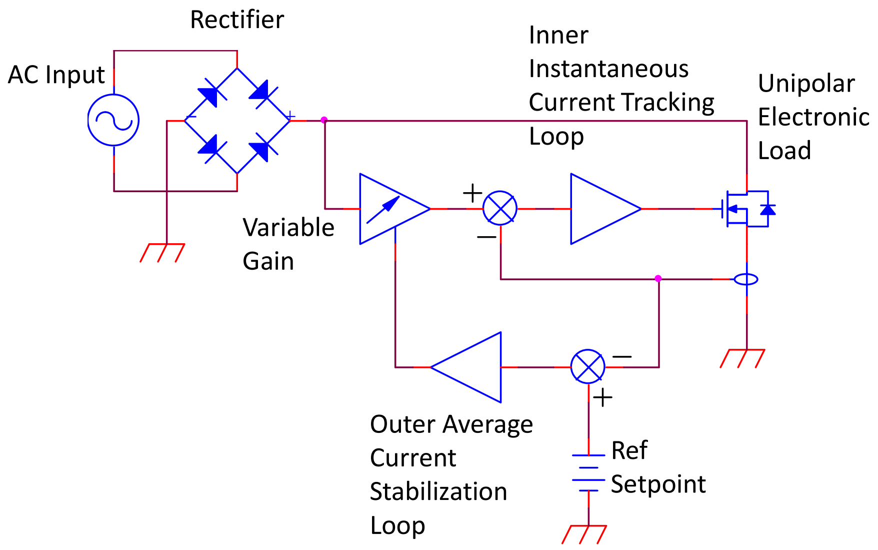
- 1. Synchronous rectifier driven unipolar electronic load
    - Convert AC into full wave rectified DC with min voltage drop, feeding electronic load circuit
        - Rectifier power train has high component count
    - Single power device electronic load
        - Handles DC only, simple control

- 2. Bipolar electronic load without need of frontend rectification
    - Electronic load circuit operates directly on incoming AC, eliminates front end rectifier and voltage drop
    - Two back-to-back MOSFETs as bidirectional electronic load power device
    - Higher component count required for AC signal processing
    - Two auxiliary power rails or more needed (+ve…/-ve)

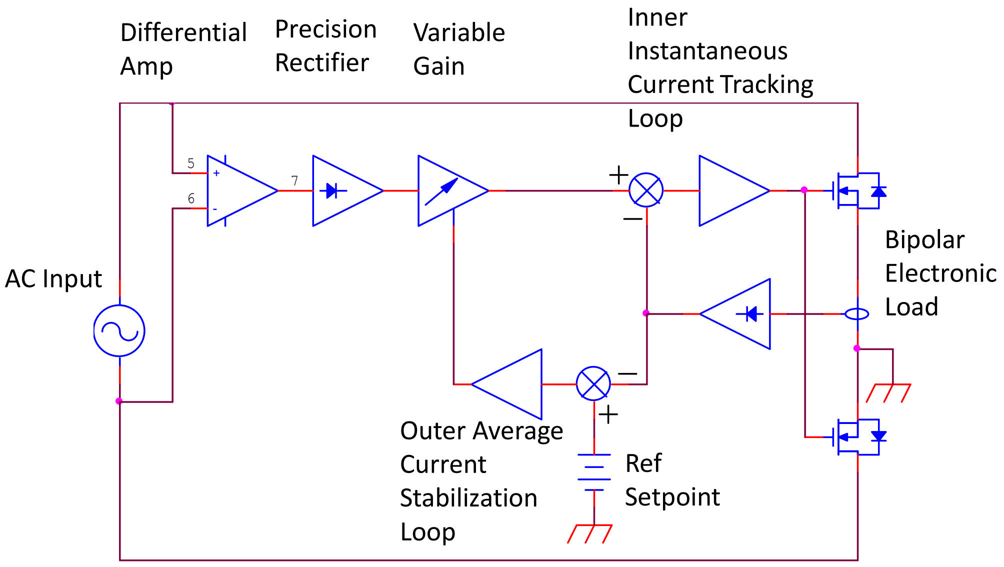
- Both approaches 1,2 require electronically controlled potentiometer circuit
    - LED coupled with CdS photocell or
    - Utilizing semiconductor controlled resistive region
    - Off the shelf potentiometer IC ?

- Simulation (LTSpice) to verify feasibility

Block diagram, Option 1 and 2

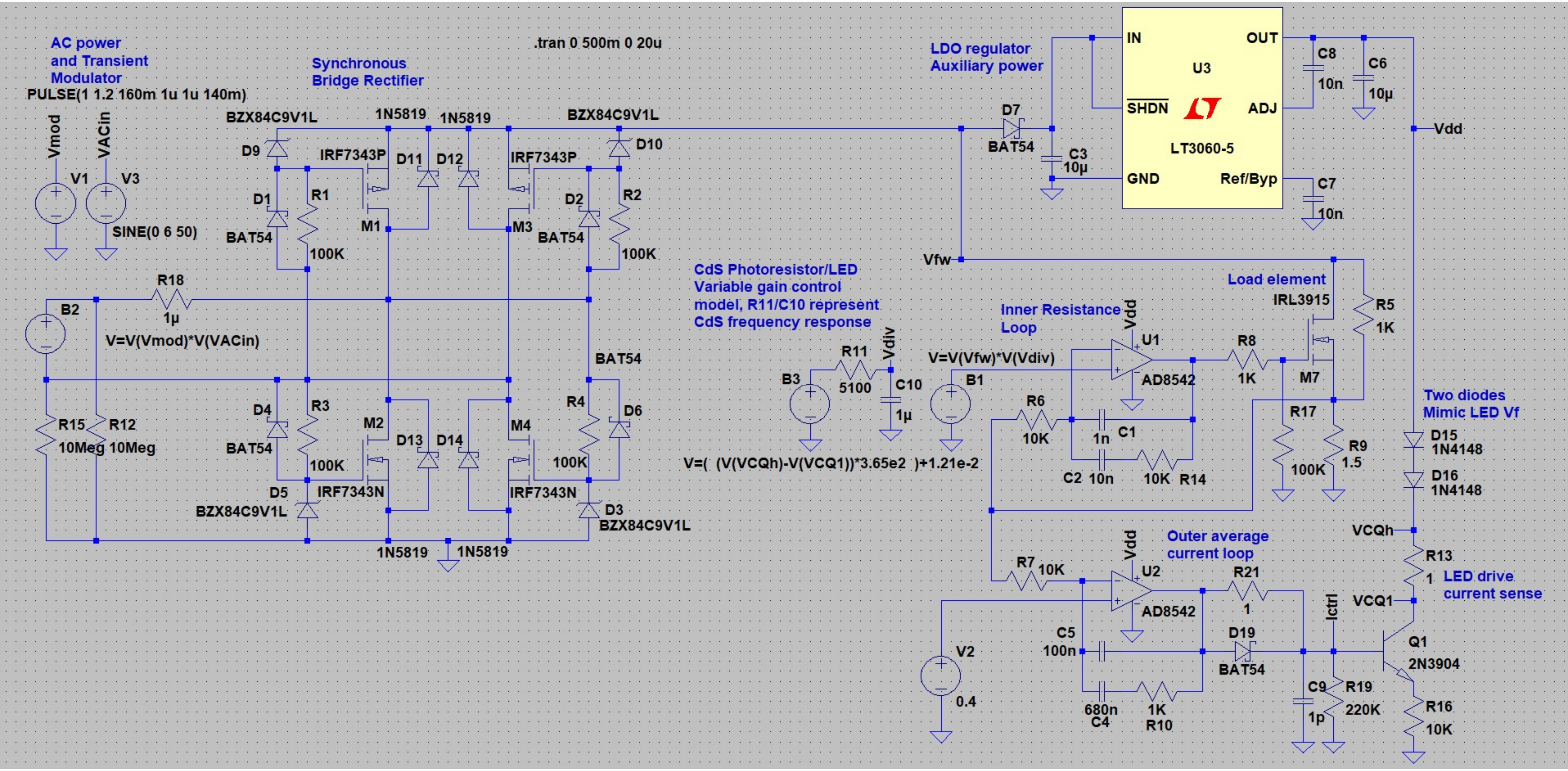


Option 1

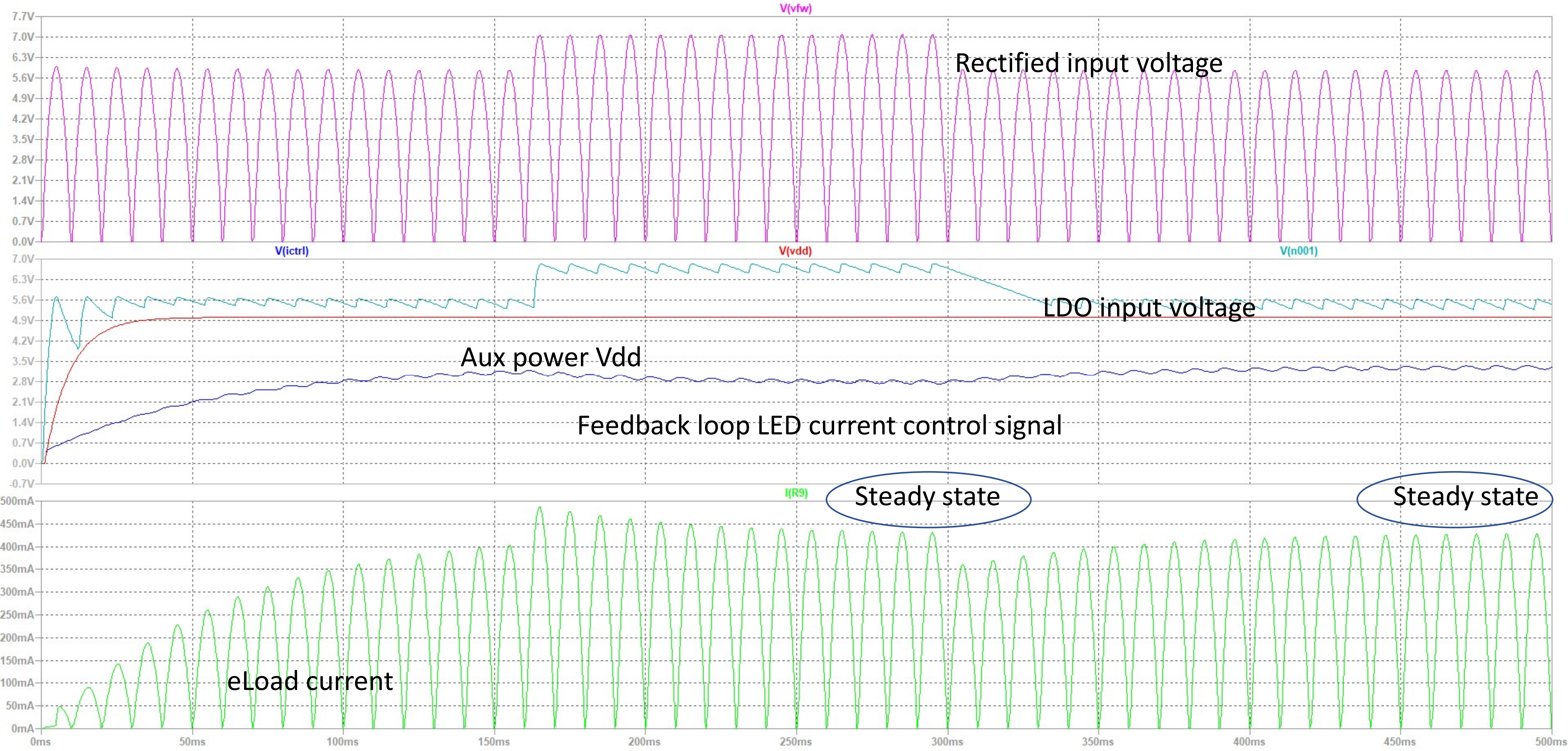


Option 2

Design option 1, SR driven electronic load, this is close approximation of application circuit



Design option 1, SR driven electronic load, simulation result



Rectified input voltage

LDO input voltage

Aux power Vdd

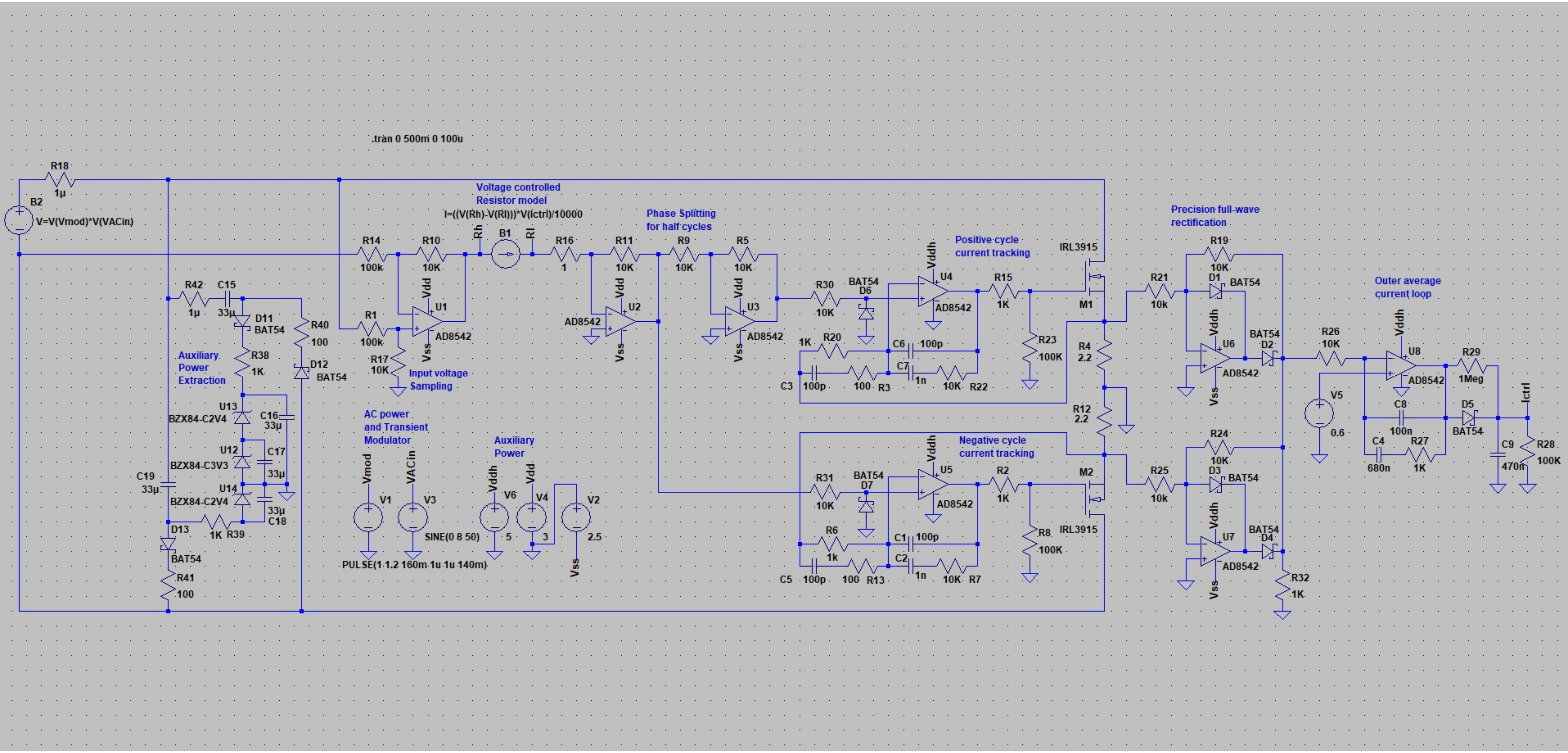
Feedback loop LED current control signal

Steady state

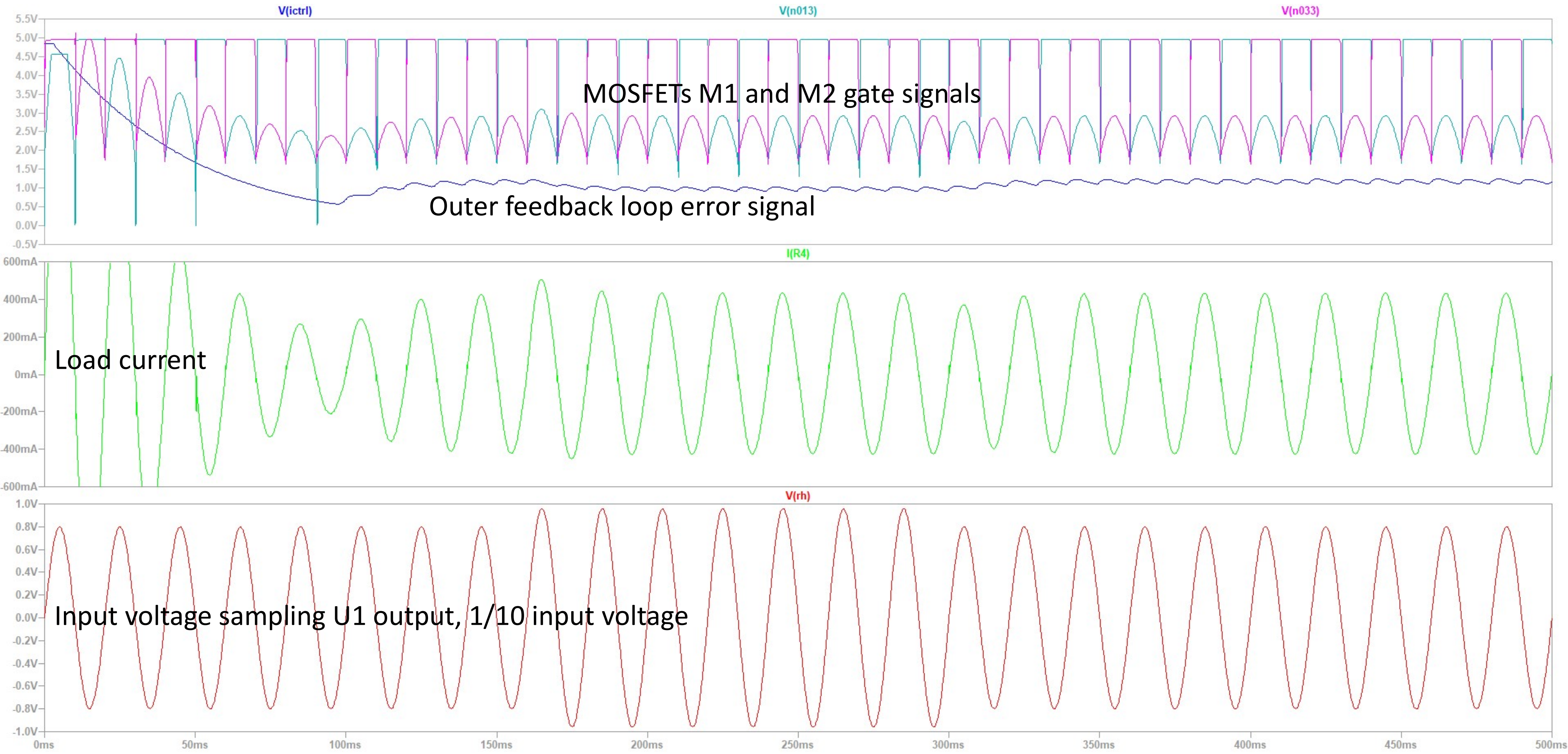
Steady state

eLoad current

Design option 2, Bipolar electronic load, some function blocks not fully expanded



Design option 2, bipolar electronic load, simulation result



MOSFETs M1 and M2 gate signals

Outer feedback loop error signal

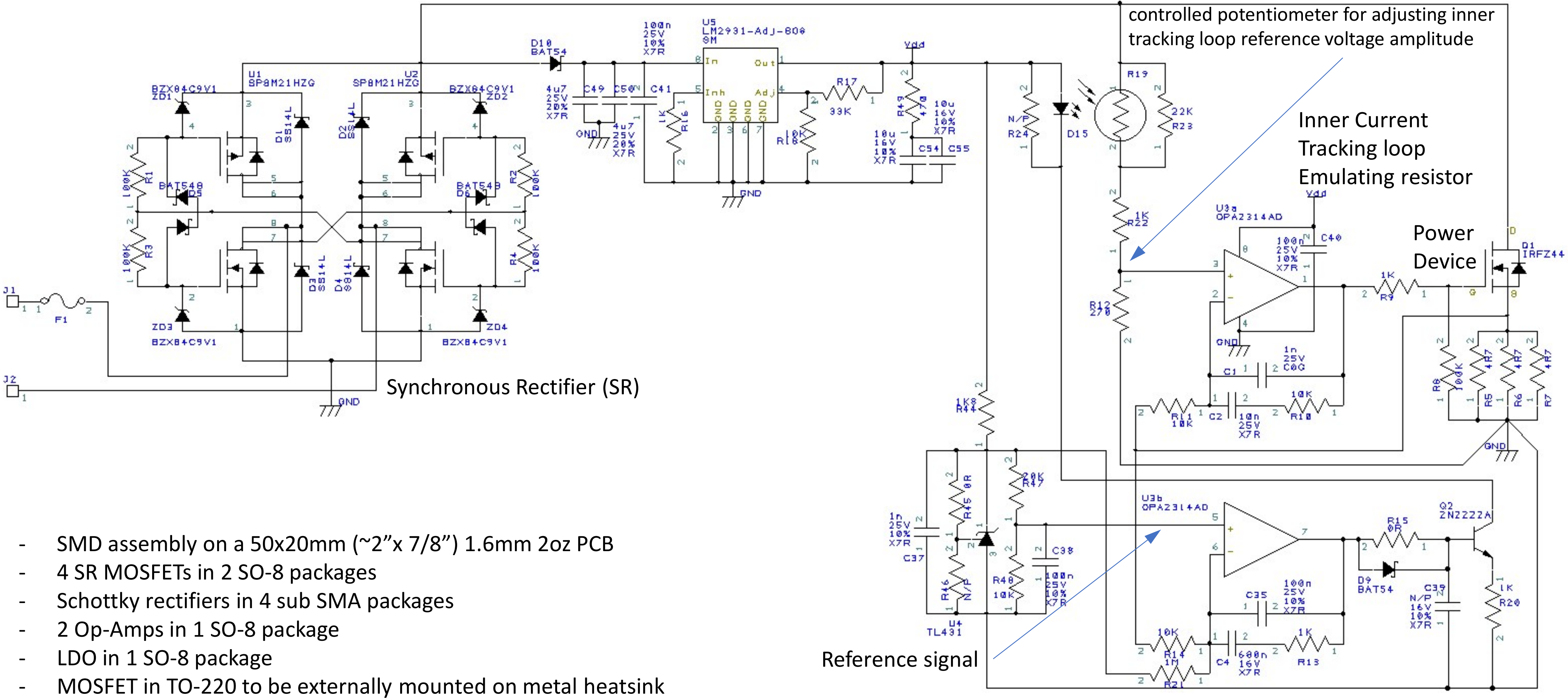
Load current

Input voltage sampling U1 output, 1/10 input voltage

Comparison:

Checklist	1, Synchronous Rectifier + unipolar electronic load	2, bipolar electronic load
Rectifier MOSFETs	4	0
Schottky Power Rectifiers	4	0
eLoad MOSFETs	1	2
Op Amps	2	8
Voltage controlled potentiometer	1	1
Aux power rails	1	3
LDOs	1	3
Practical design SO-8 packages	4	5
Practical design TO-220 packages	1	2
Current distortion	Cross-over distortion exists	Lower distortion
Complexity power section	High	Low
Complexity control section	Low	High
Complexity auxiliary power	Low	High
Select for build	Selected	

Option 1 practical circuit implementation



Auxiliary power

Current control resistor as part of voltage-controlled potentiometer for adjusting inner tracking loop reference voltage amplitude

Inner Current Tracking loop Emulating resistor

Power Device

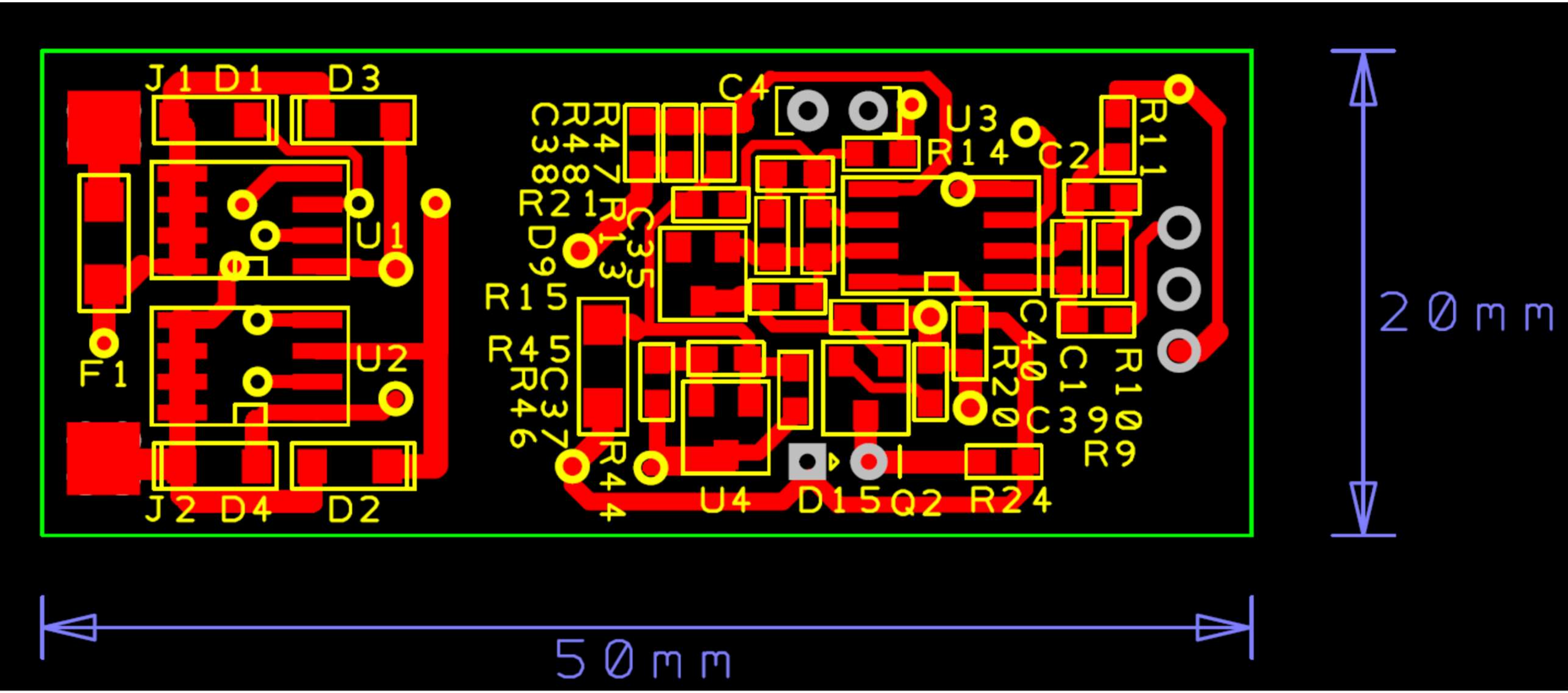
Synchronous Rectifier (SR)

Reference signal

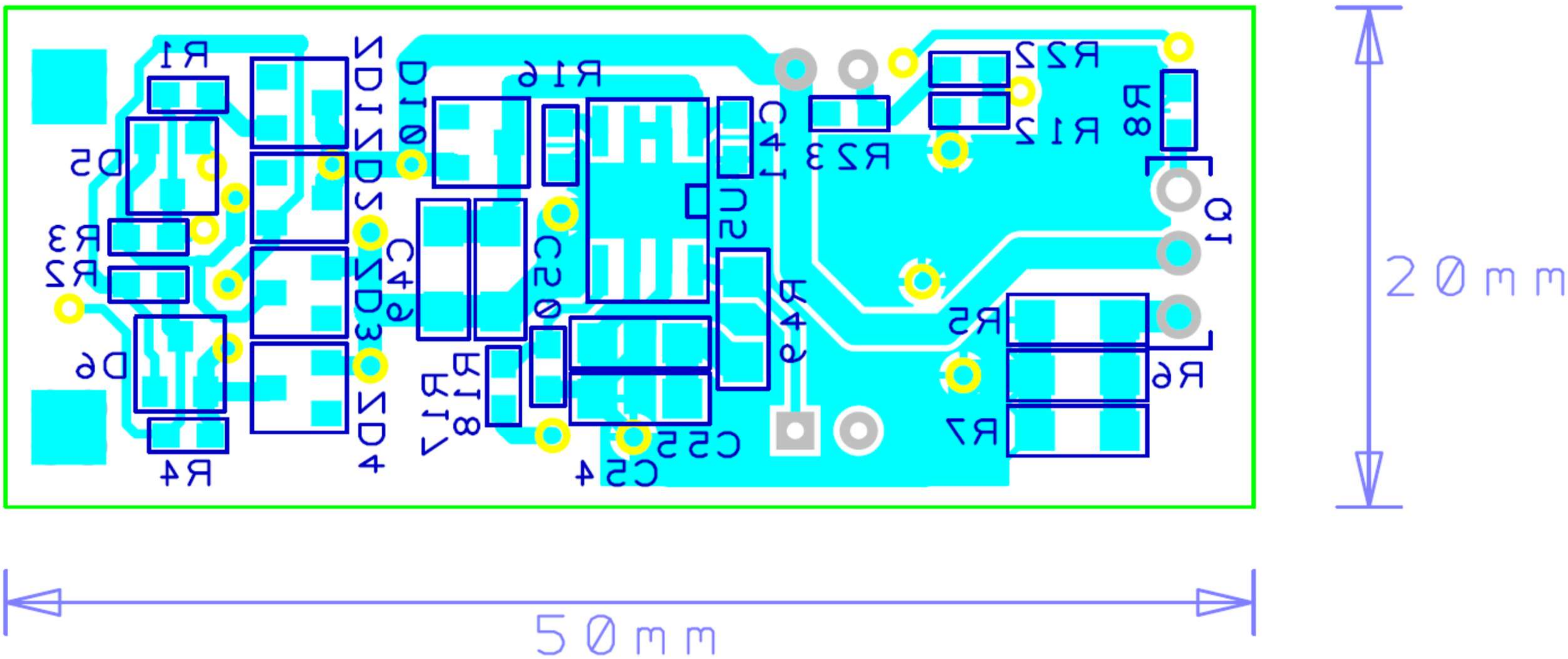
Outer average current loop
Bandwidth < 25Hz, varying inner loop resistance to regulate current

- SMD assembly on a 50x20mm (~2”x 7/8”) 1.6mm 2oz PCB
- 4 SR MOSFETs in 2 SO-8 packages
- Schottky rectifiers in 4 sub SMA packages
- 2 Op-Amps in 1 SO-8 package
- LDO in 1 SO-8 package
- MOSFET in TO-220 to be externally mounted on metal heatsink
- Current controlled resistor is a custom-made LED/CdS assembly

PCB layout, top side, synchronous rectifier, reference, control loops and eLoad MOSFET



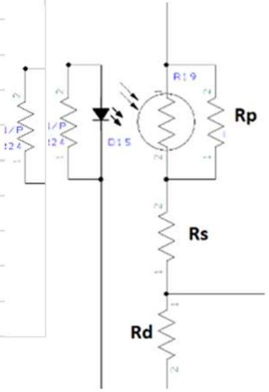
PCB layout, bottom side, synchronous rectifier signal components, aux power, current sense and misc control loop components



Current controlled resistor for changing inner current tracking loop (D15/R19 on schematic) AC reference signal

- LED illuminating a CdS photocell packaged in a light tight housing
- To fit the present PCB dimension, 3mm LED and 5mm CdS photocell are selected, housing measures 10x10x10mm

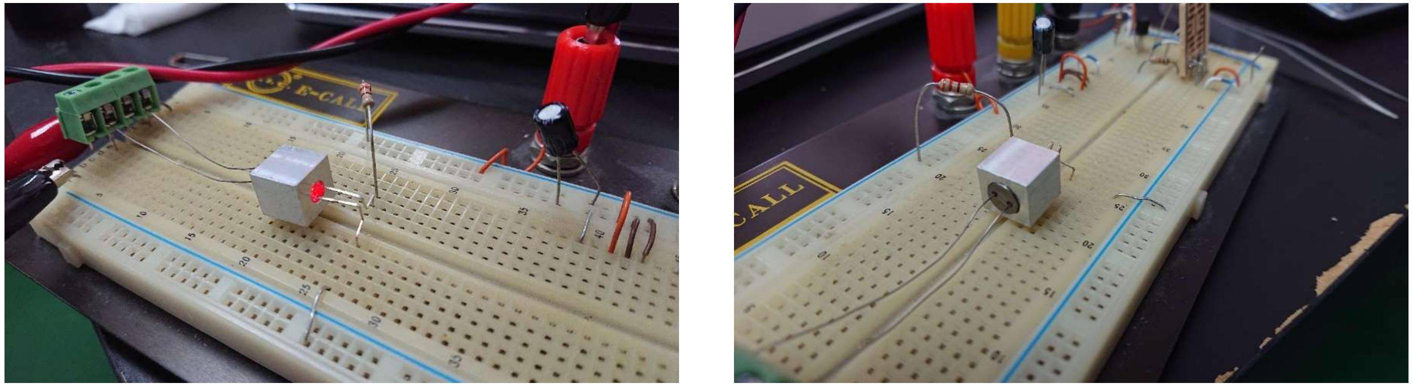
CdS Photocell resistance vs LED current, 23-Apr-2021, Virgil Cheng					
CdS device		Unknown manufacturer 5mm hermatic package			
LED		Different types			
Package		Aluminium block, light tight enclosure during test			
Rs	1000		LED current	Iwatsu	VOAC7602
Rp	22000		Resistance	HP	3486A
Rd	270				
Ratio base	1.16E-02	used on LTSpice modelling			
ratio/curr	2.55E+02	used on LTSpice modelling			



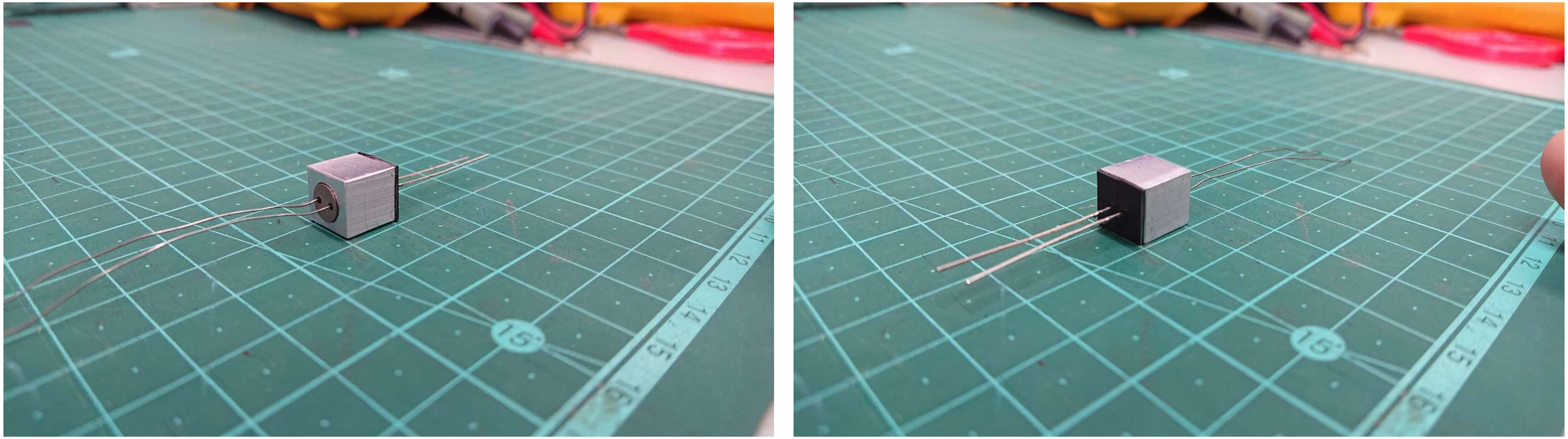
Voltage divider and useful component parameter based on 3TF7 and 1HT4 specification

Part number	3TF7	1HT4	
Current	0.3	0.1	A
Min Vin	7	4	VACRMS
Power	5	5	W
min volt power disp	2.1	0.4	W
max Pd voltage	16.66667	50	VACRMS
const I ref voltage	0.6	0.6	VDC
min Volt pk	9.898	5.656	VDC
min Volt avg	4.50359	4.50359	VDC
min Vin attn factor	0.133227	0.133227	
min Vin RCdS Pd	0.020957	0.006843	W
max Volt pk	23.56667	70.7	VDC
max Volt avg	15.01197	45.0359	VDC
max Vin attn factor	0.039968	0.013323	
max Vin RCdS Pd	0.039476	0.121715	W

With 0.6V represent spec current, 3TF7 requires voltage divider ratio between 0.04 and 0.13

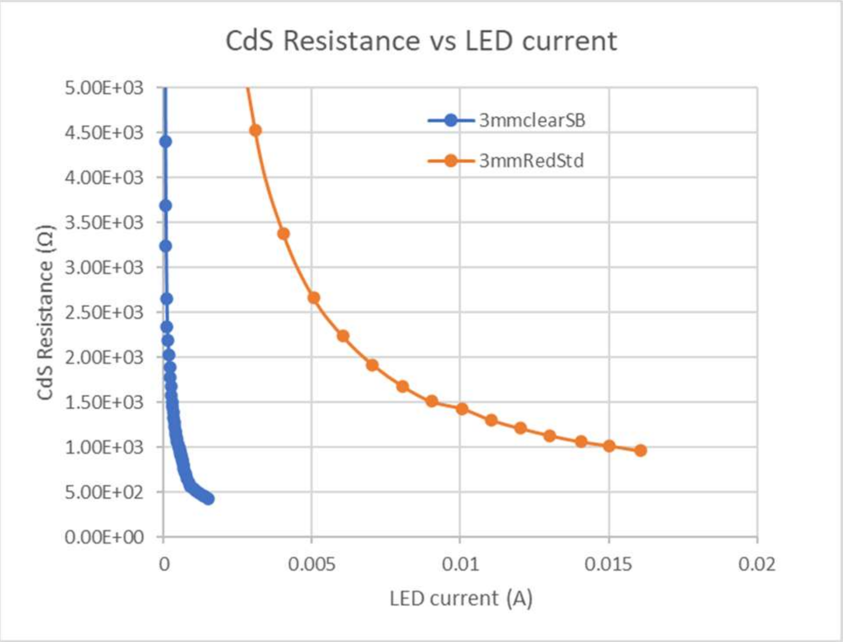


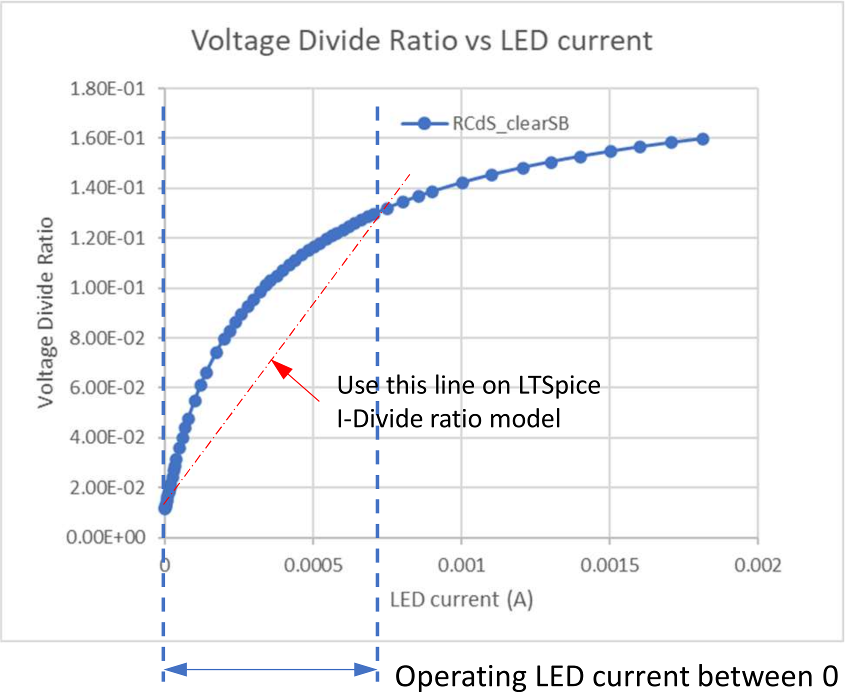
UUT was covered with a light-tight enclosure during test



Complete CdS photocell - LED assembly with light shield at LED end

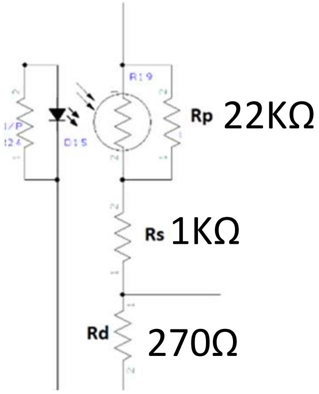
Current controlled resistor measurement result resultant linearized voltage divider characteristic





Use this line on LTSpice
I-Divide ratio model

Operating LED current between 0 to ~700uA

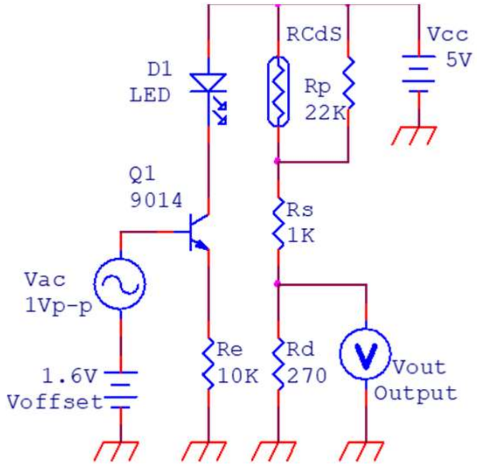


- There is dramatic efficacy difference between superbright LED and standard LED, superbright LED achieves minimum resistance with just 1mA driving current.
- Clear superbright LED to be used in prototype
- LTSpice simulation model used approximated linear parameter generated from measurement result, loop stability confirmed

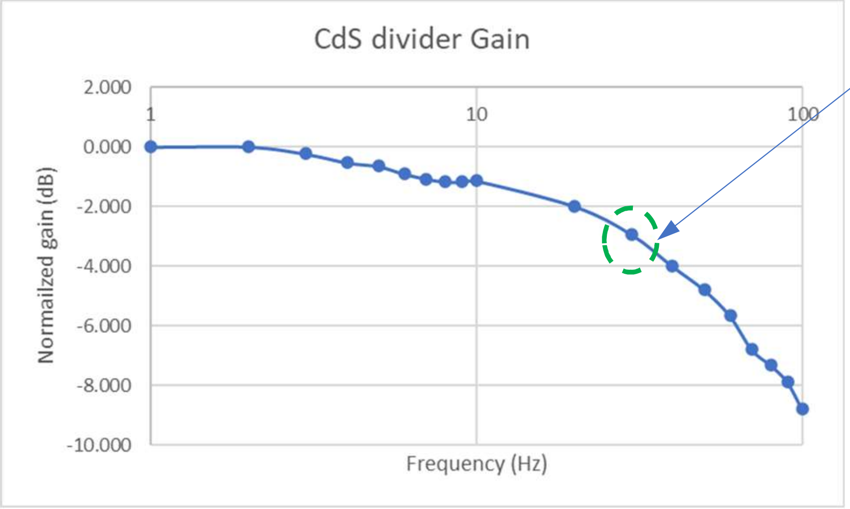
Small signal AC response – Current -> Resistance AC transfer characteristic

CdS Photocell voltage divider dynamic response, 28-Apr-2021, Virgil Cheng						
CdS device		Unknown manufacturer 5mm hermatic package				
LED		Different types				
Package		Aluminium block, light tight enclosure during test				
Rs	1000		Signal source	HP	33120A	
Rp	22000		Phase/Gain	Rigol	DS1102E	
Rd	270					
Vac	1	Vp-p				
Voffset	1.6V	DC				

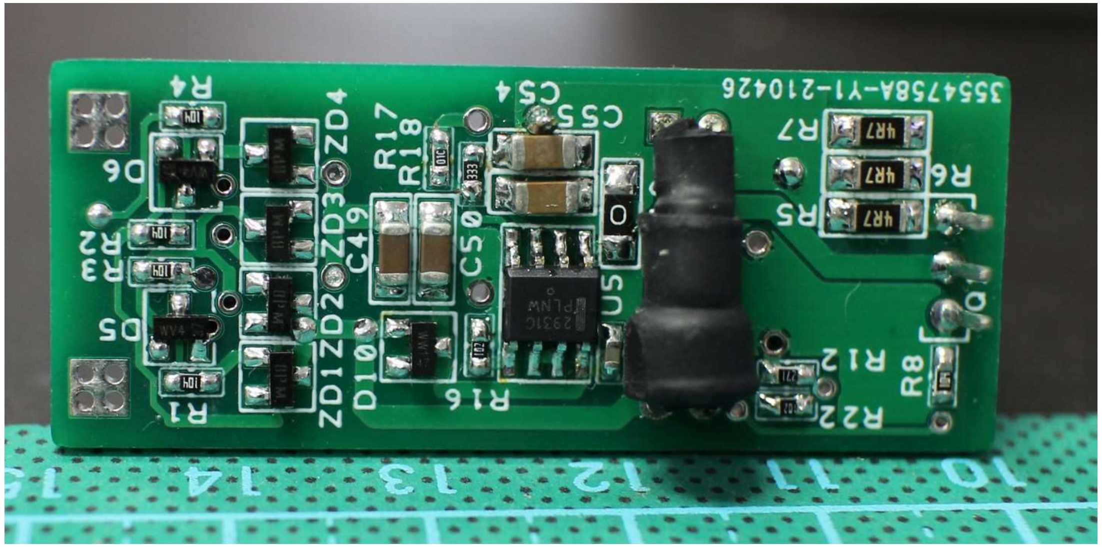
Freq	Vin	Vout	Phase	Gain	Gain
Hz	Vp-p	Vp-p	Lag°	dB	1Hz baseline
1	1.04	0.146	-5	-17.054	0.000
2	1.04	0.146	-2	-17.054	0.000
3	1.04	0.142	0	-17.295	-0.241
4	1.06	0.14	1	-17.584	-0.530
5	1.06	0.138	2	-17.709	-0.655
6	1.06	0.134	3	-17.964	-0.910
7	1.08	0.134	4	-18.126	-1.073
8	1.06	0.13	6	-18.227	-1.174
9	1.06	0.13	7	-18.227	-1.174
10	1.04	0.128	9	-18.196	-1.143
20	1.04	0.116	21	-19.052	-1.998
30	1.04	0.104	31	-20.000	-2.946
40	1.04	0.092	34	-21.065	-4.011
50	1.04	0.084	43	-21.855	-4.801
60	1.04	0.076	47	-22.724	-5.671
70	1.06	0.068	52	-23.856	-6.802
80	1.06	0.064	57	-24.383	-7.329
90	1.06	0.06	58	-24.943	-7.889
100	1.06	0.054	60	-25.858	-8.805

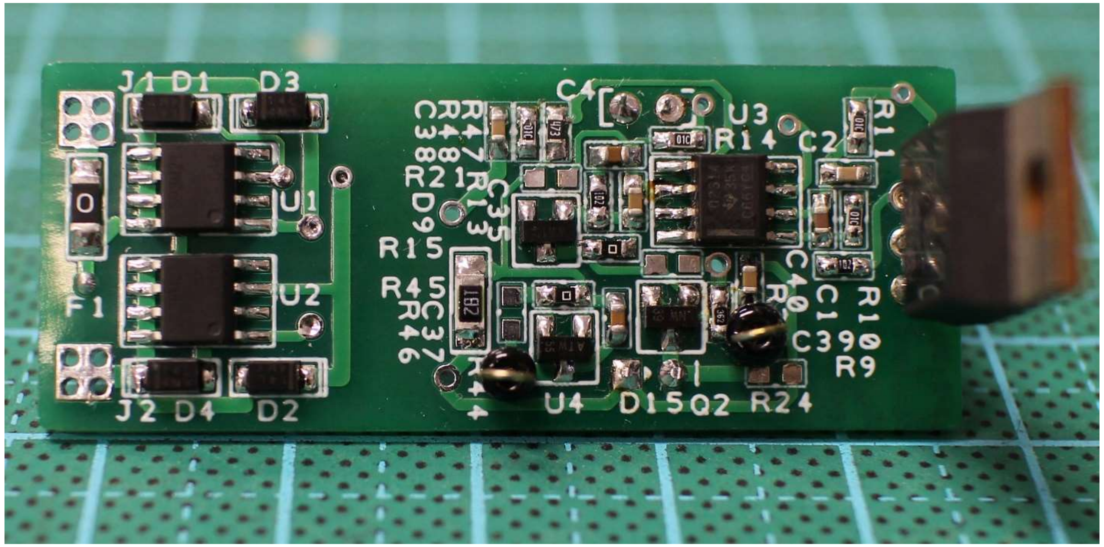


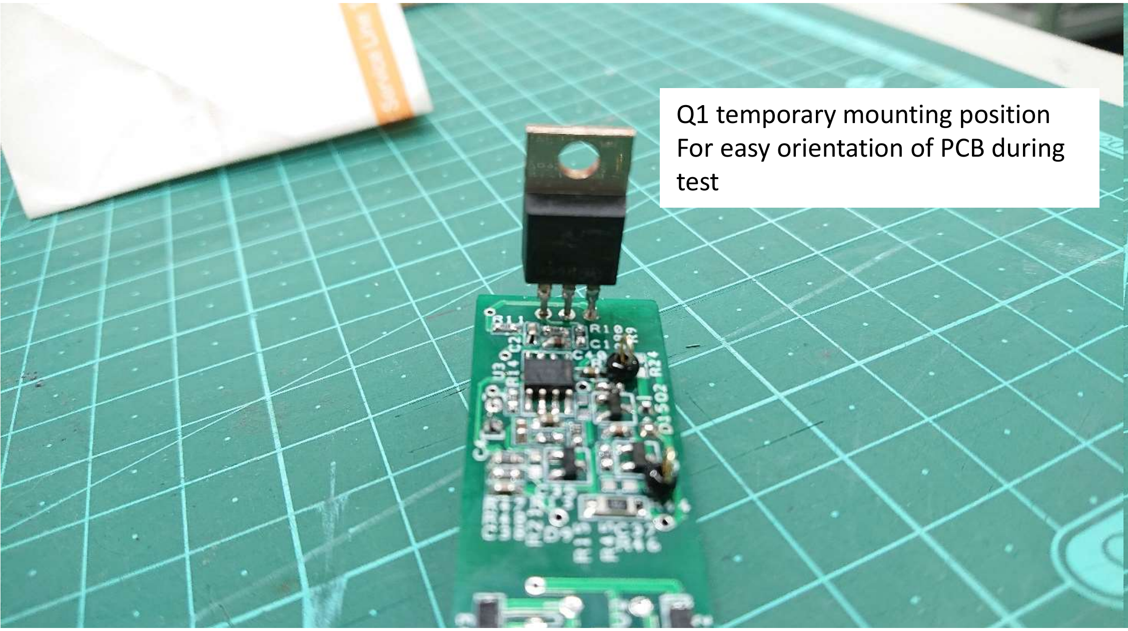
-3dB @30Hz



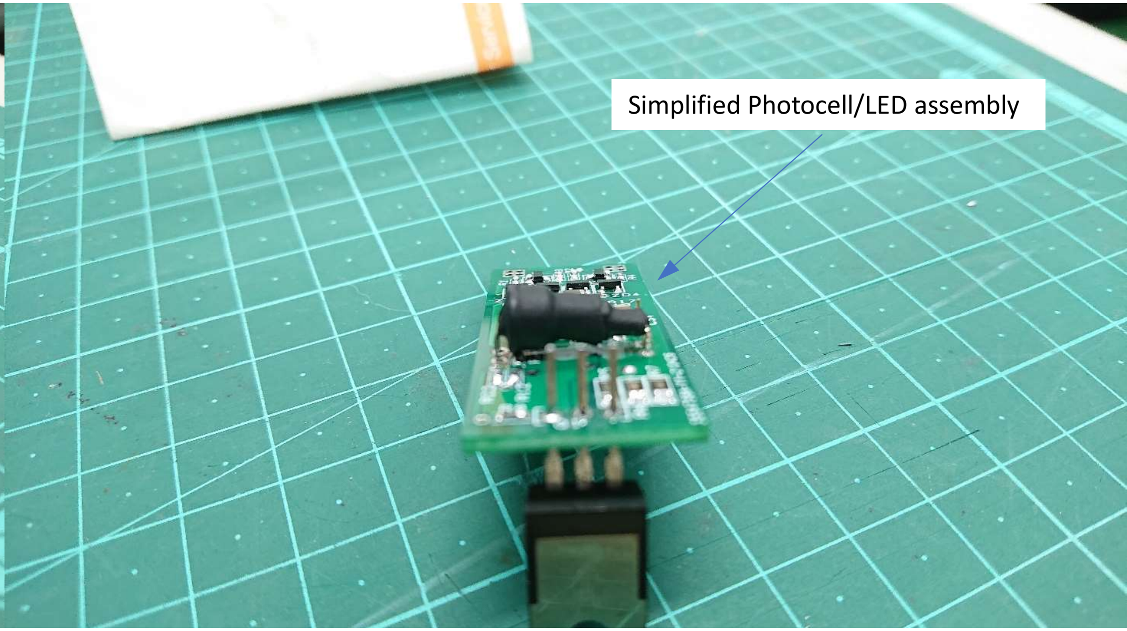
PCB Assembly build



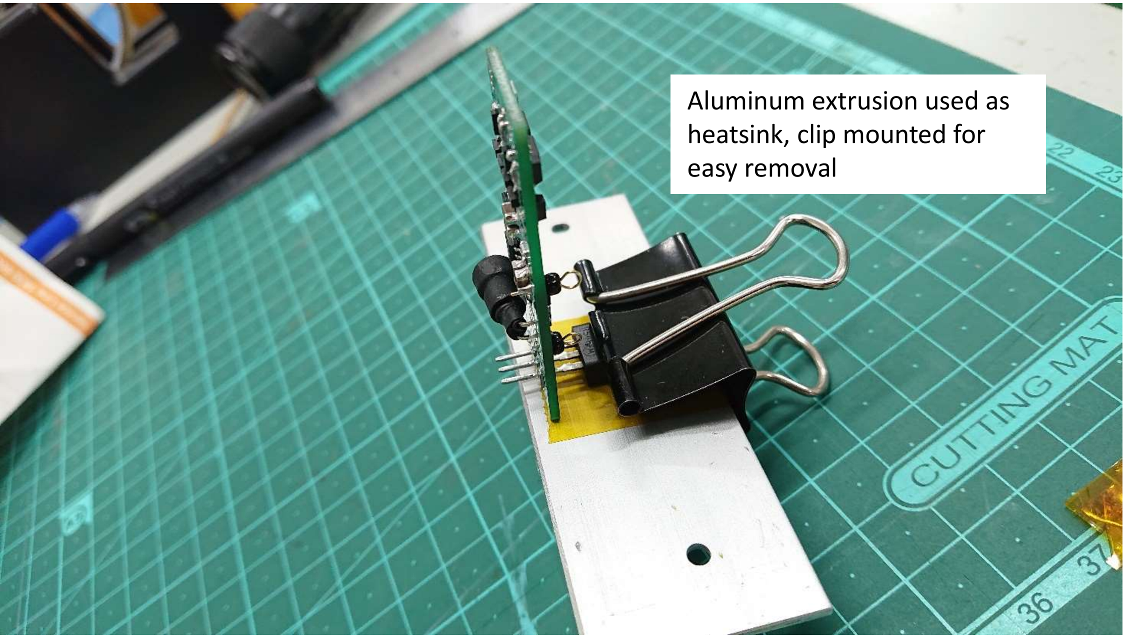




Q1 temporary mounting position
For easy orientation of PCB during test

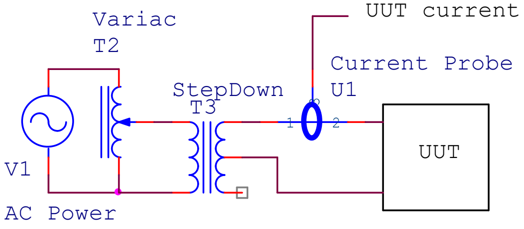


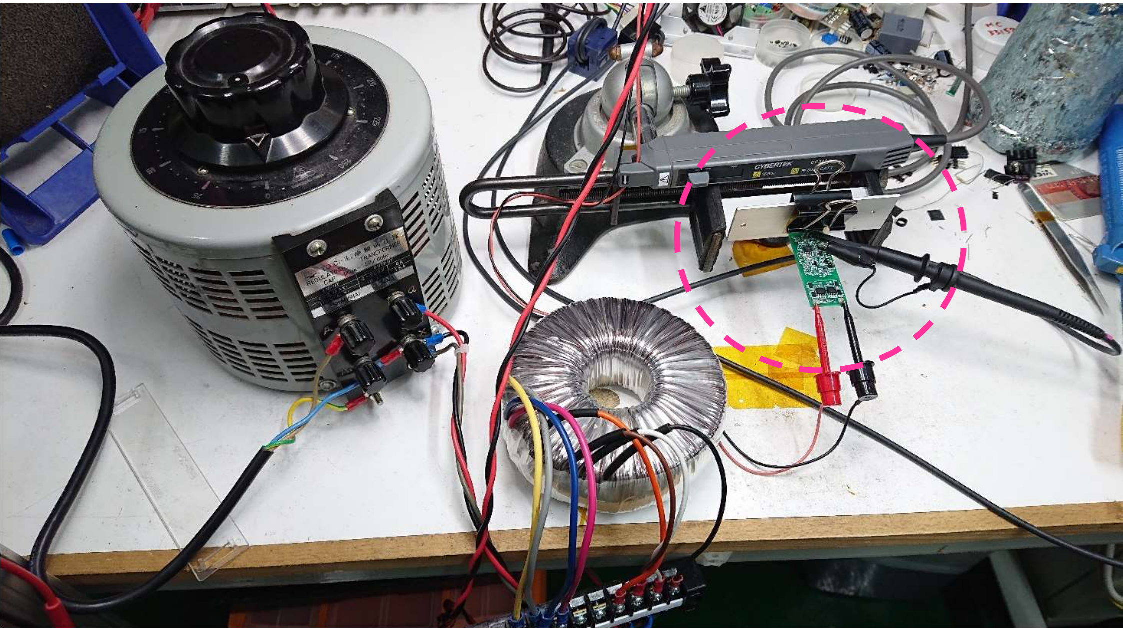
Simplified Photocell/LED assembly



Aluminum extrusion used as heatsink, clip mounted for easy removal

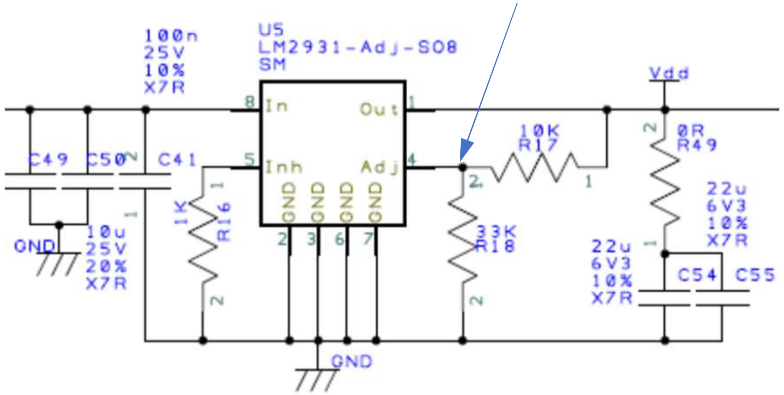
Test Setup

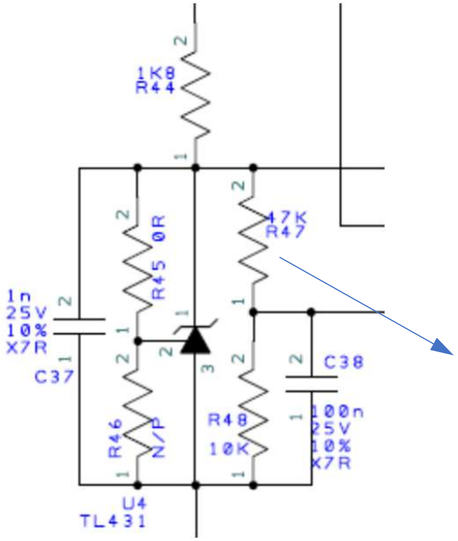




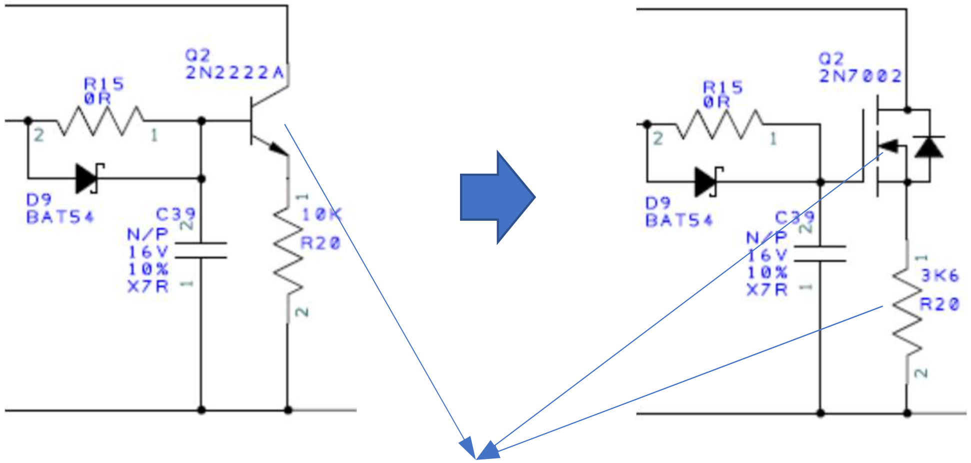
Debugging/Corrections

R17/R18 value corrected
Voltage divider was inverted





R47 changed to 47K
For 300mA current



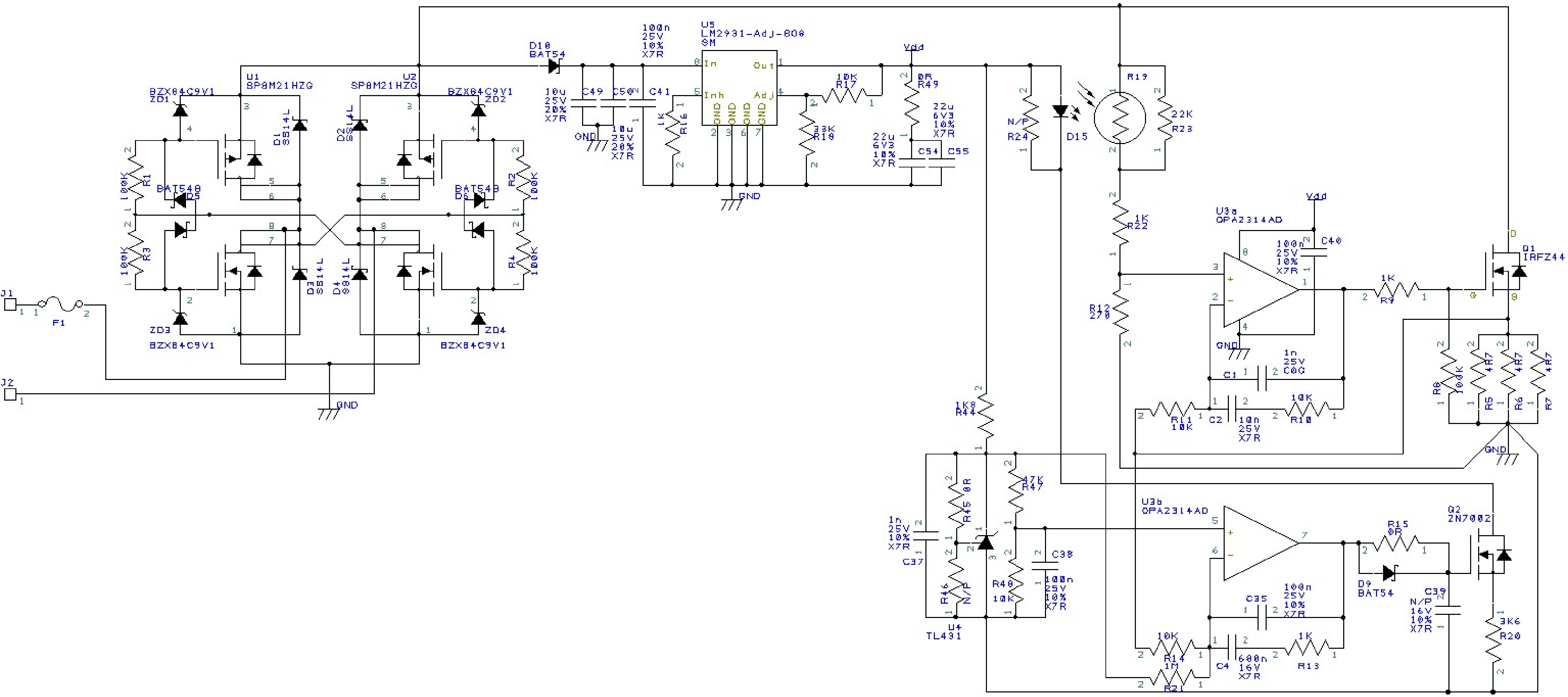
Q2 change from BJT to MOSFET

- During test and slow startup U3b output can reach Vdd
- With NPN transistor, BC junction can be forward biased forcong LED cathode to high level blocking LED from conduction, unit became latched at low current level
- Changing Q2 to MOSFET eliminates this problem

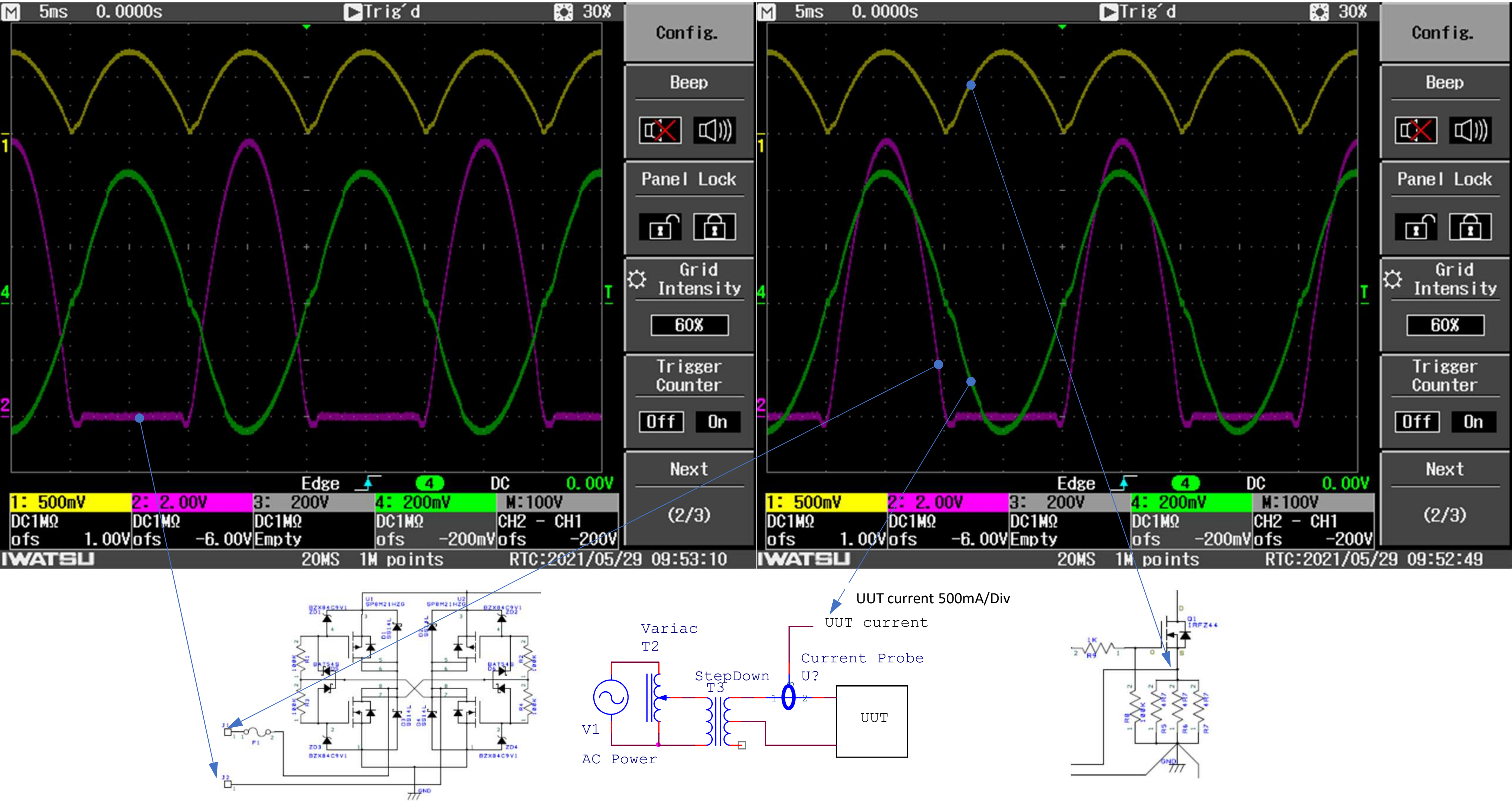
R20 Reduced from 10K to 3K6

- MOSFET requires Vth higher than BJT one diode drop
- This reduces source voltage level and provide enough headroom for MOSFET bias

Final schematic



Test Waveform, input side, 7VAC input (2nd set taken 29-may-2021 using AC source, replace old measurement using variac)

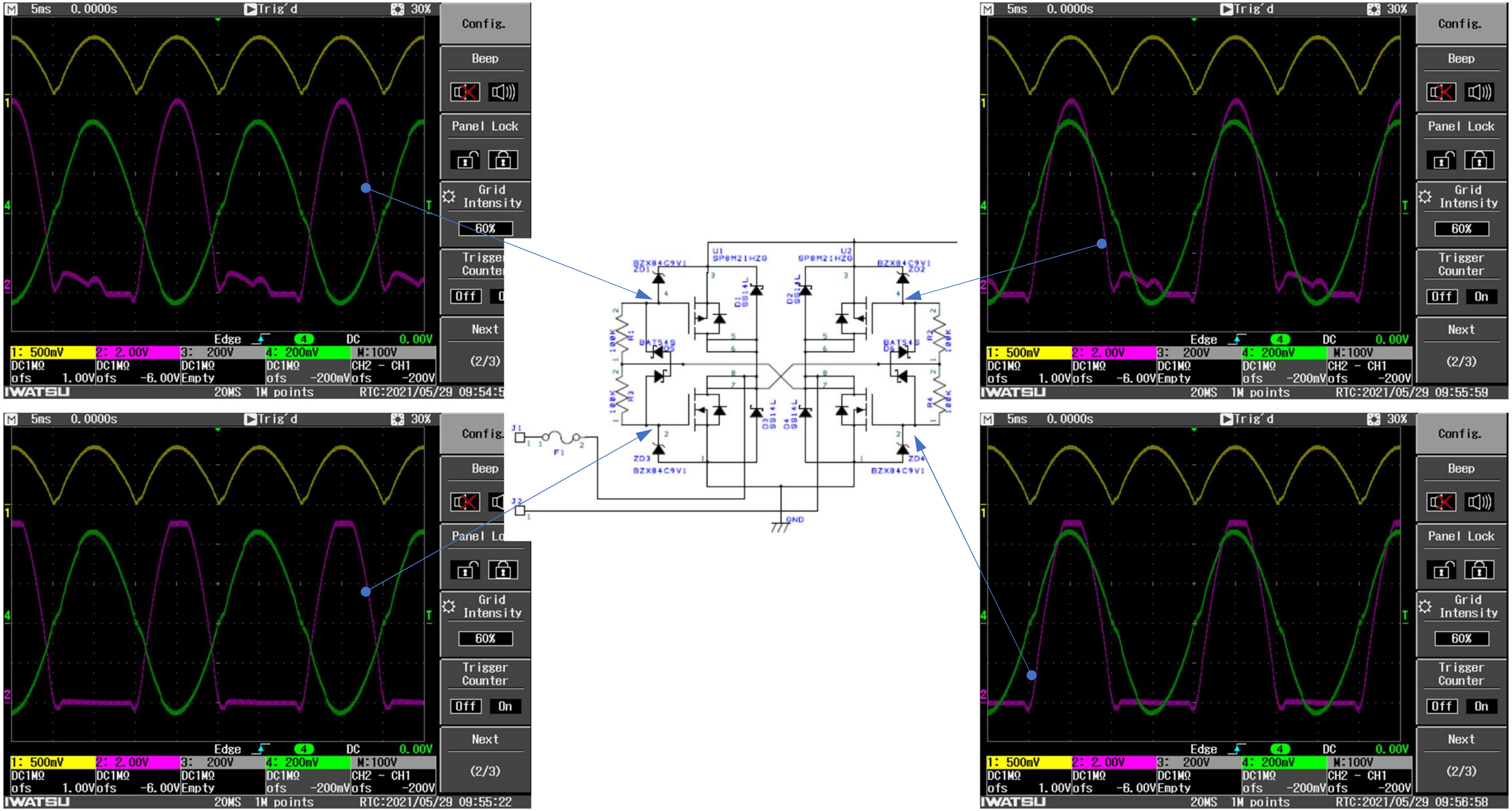


M 5ms 0.0000s Trig´d 30%
Edge 4 DC 0.00V
1: 500mV DC1MΩ ofs 1.00V
2: 2.00V DC1MΩ ofs -6.00V
3: 200V DC1MΩ Empty
4: 200mV DC1MΩ ofs -200mV
M:100V CH2 - CH1 ofs -200V
Grid Intensity 60%
IWATSU 20MS 1M points RTC:2021/05/29 09:53:10

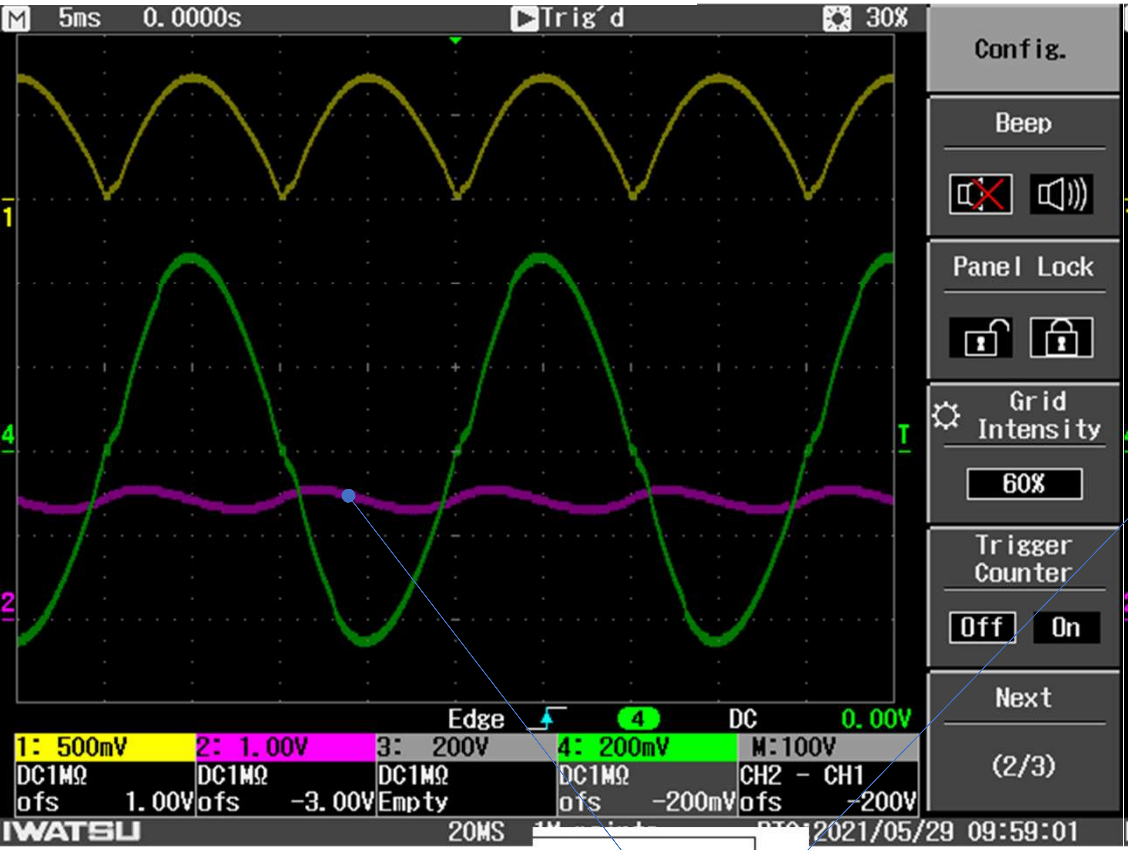
M 5ms 0.0000s Trig´d 30%
Edge 4 DC 0.00V
1: 500mV DC1MΩ ofs 1.00V
2: 2.00V DC1MΩ ofs -6.00V
3: 200V DC1MΩ Empty
4: 200mV DC1MΩ ofs -200mV
M:100V CH2 - CH1 ofs -200V
Grid Intensity 60%
IWATSU 20MS 1M points RTC:2021/05/29 09:52:49

UUT current 500mA/Div

Test Waveform, Synchronous Rectifier Gate drive signals



Test Waveform, Photocell/LED drive

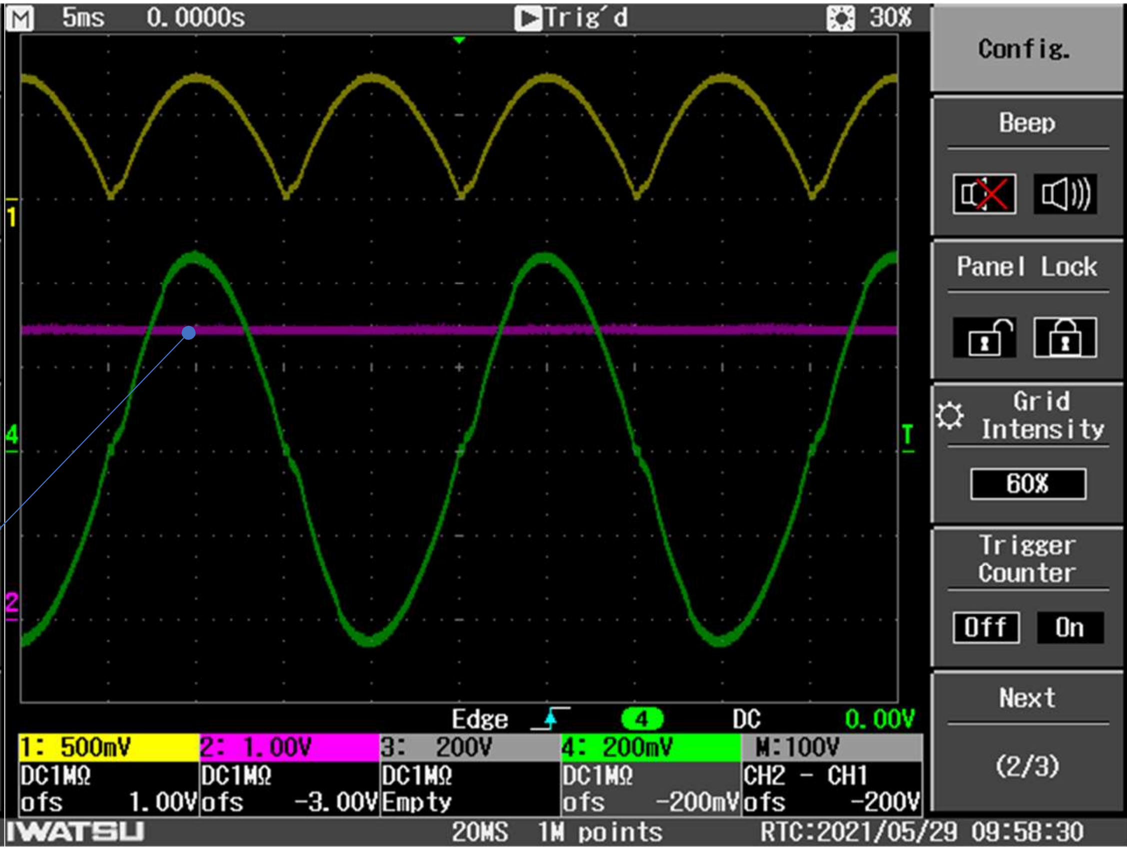


M 5ms 0.0000s ▶Trig´d 30%

Edge 4 DC 0.00V

1: 500mV	2: 1.00V	3: 200V	4: 200mV	M:100V
DC1MΩ	DC1MΩ	DC1MΩ	DC1MΩ	CH2 - CH1
ofs 1.00V	ofs -3.00V	Empty	ofs -200mV	ofs -200V

IWATSU 20MS RTC:2021/05/29 09:59:01

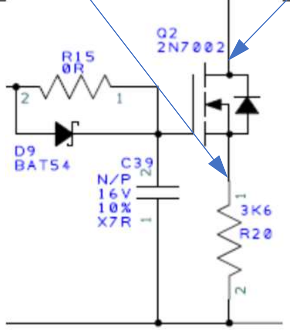


M 5ms 0.0000s ▶Trig´d 30%

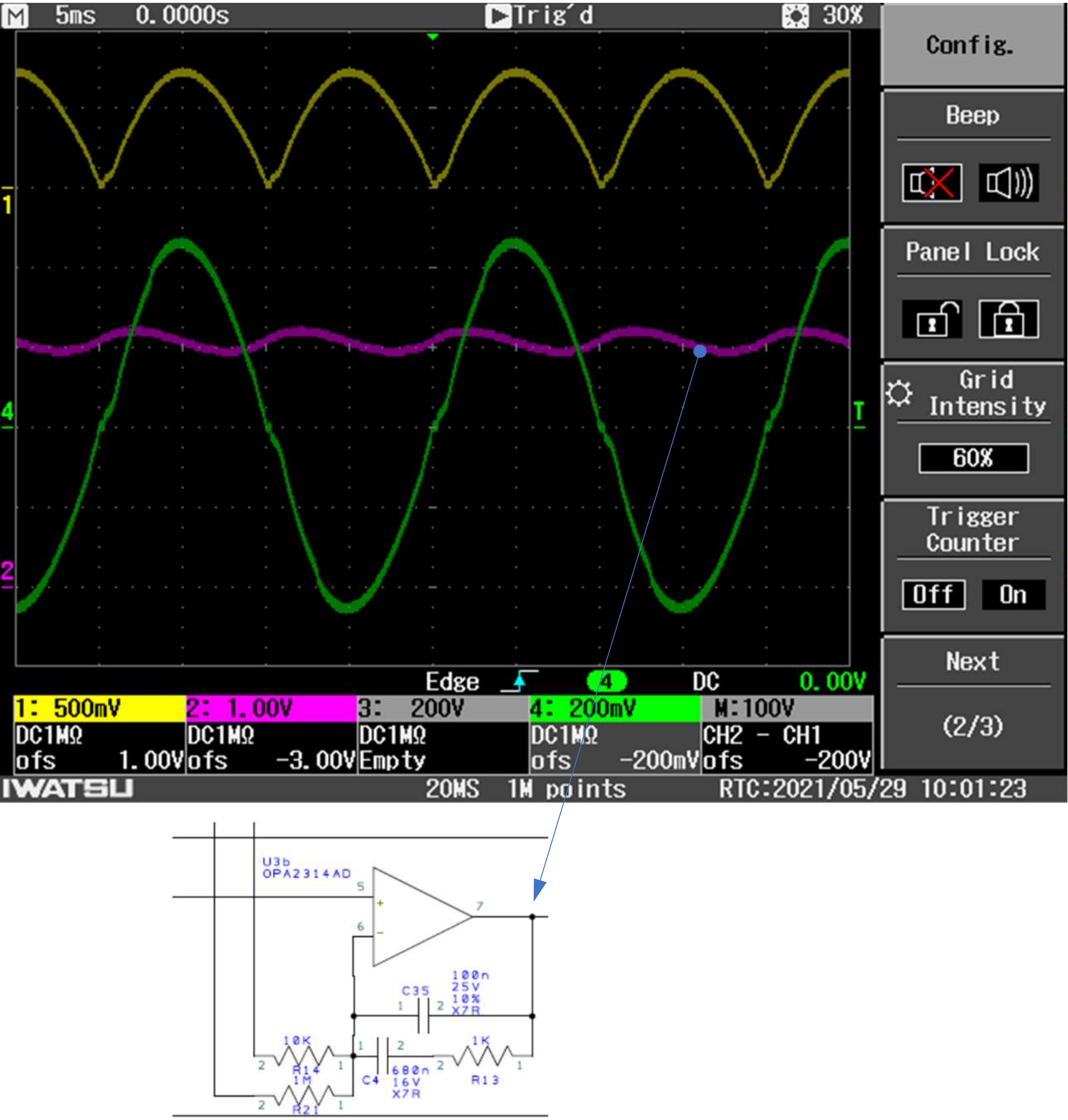
Edge 4 DC 0.00V

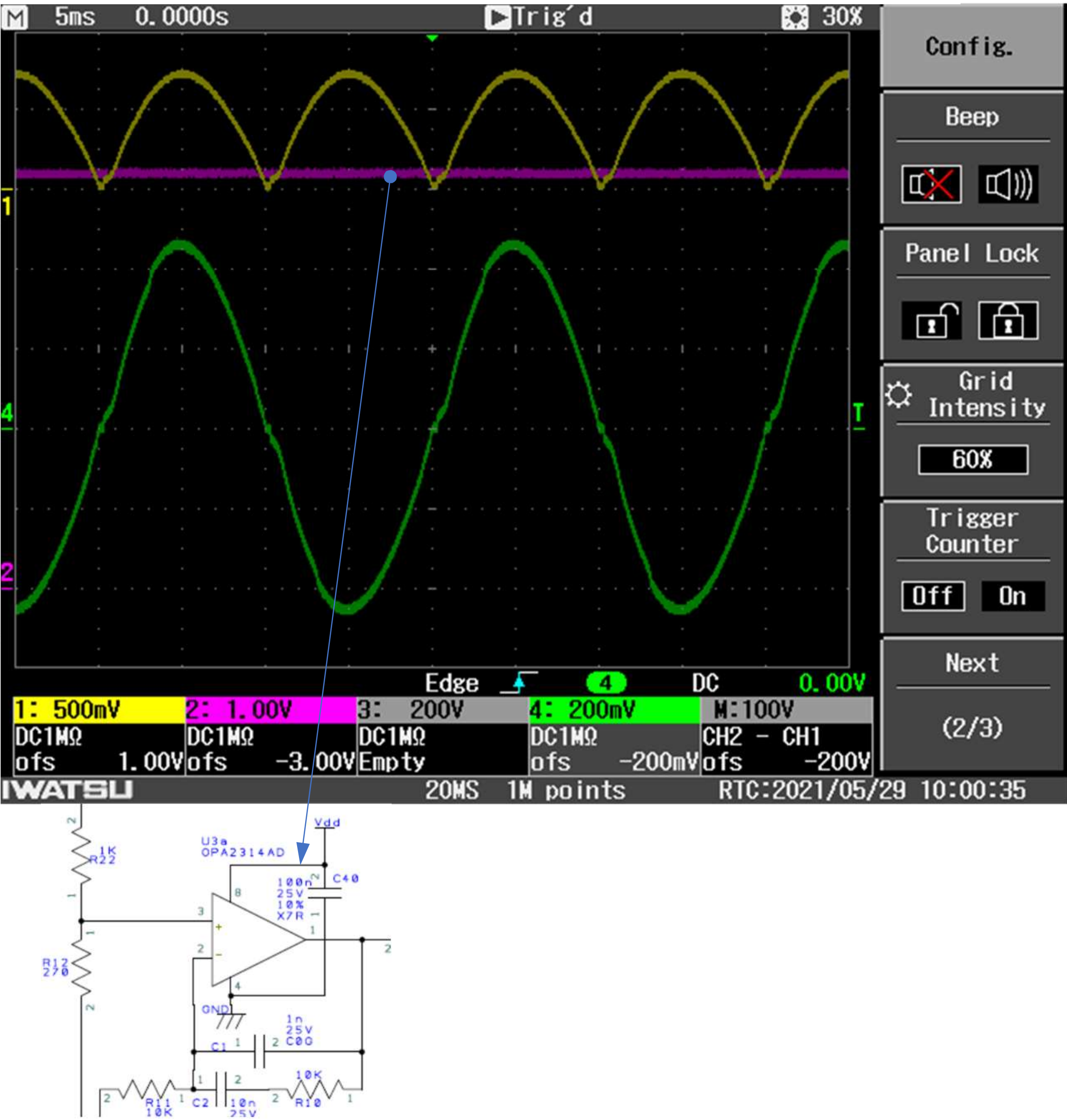
1: 500mV	2: 1.00V	3: 200V	4: 200mV	M:100V
DC1MΩ	DC1MΩ	DC1MΩ	DC1MΩ	CH2 - CH1
ofs 1.00V	ofs -3.00V	Empty	ofs -200mV	ofs -200V

IWATSU 20MS 1M points RTC:2021/05/29 09:58:30



Test Waveform, U3b outer loop error amplifier and Vdd power rail



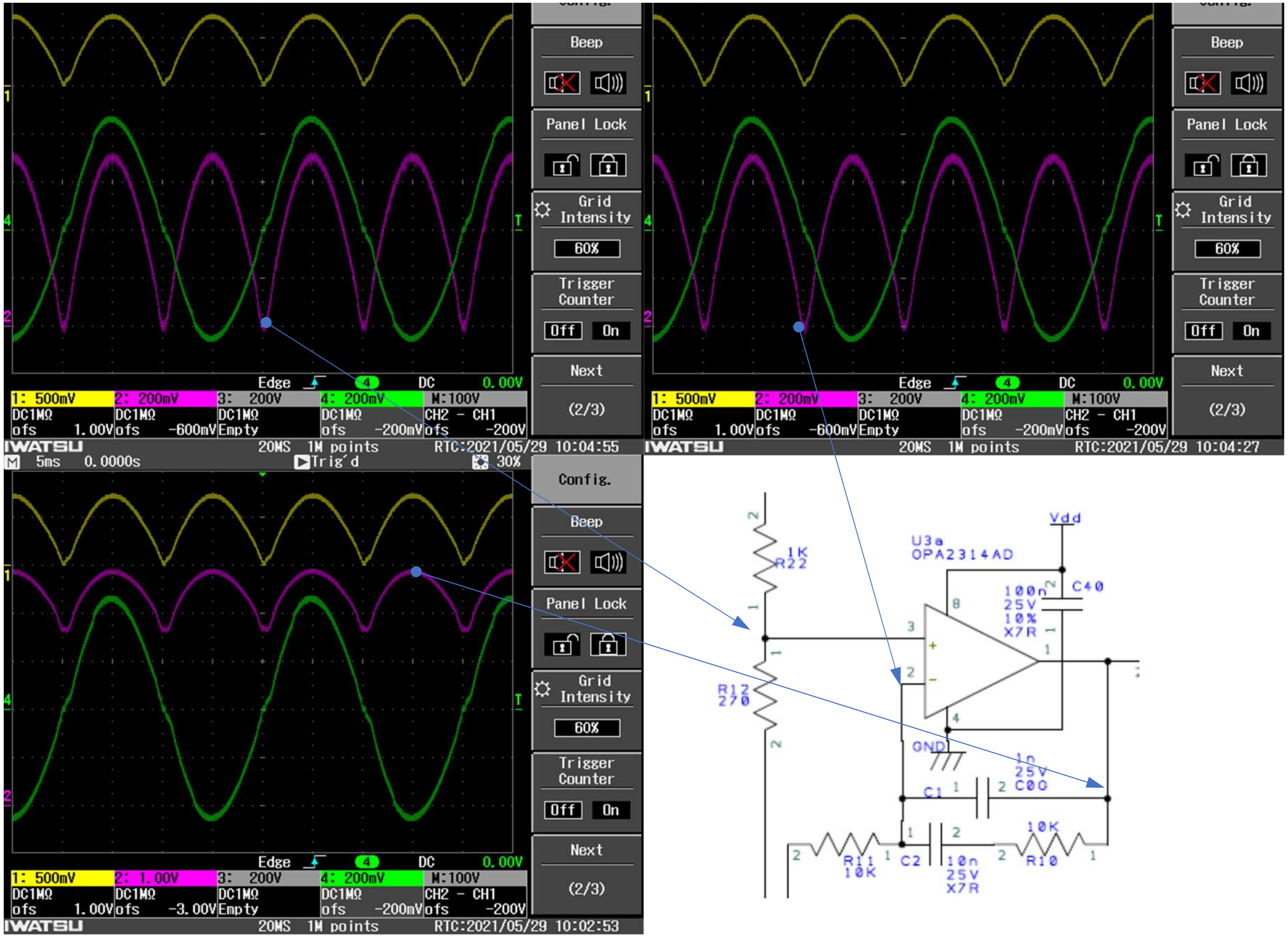


Test Waveform, U3a inner loop current tracking amplifier

Ch2-
U3a +input

Ch2-
U3a -input

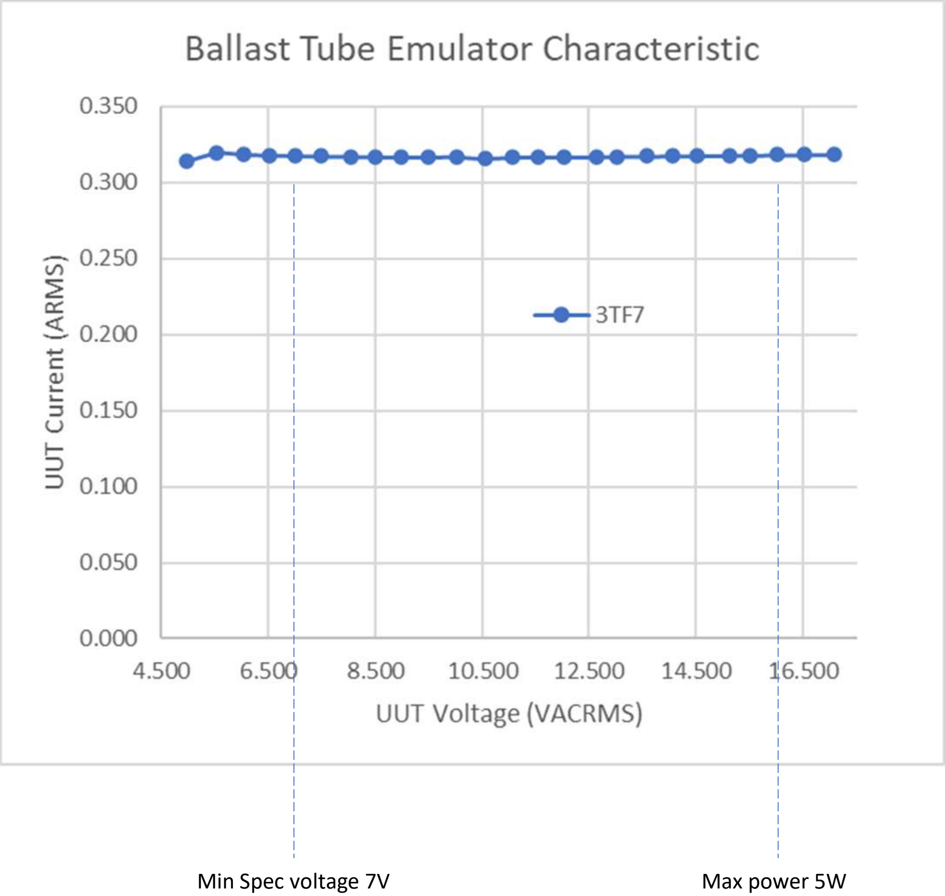
Ch2-
U3a -out



Test Data, complete unit

Solid State Ballast Test Data				
Configuration		3TF7		
Current	0.3	A		
Vmin	7	V		
Pmax	5	W		
Freq	50	Hz		
Reading	Voltage	Iwatsu	VOAC7602	100V AC
Reading	Current	Iwatsu	VOAC7602	1A
By:	Virgil Cheng		Date	10-May-21

Voltage	Current	Power	Deviation
VACRMS	ARMS	W	%tage
4.973	0.314	1.560	-1.03%
5.541	0.319	1.768	0.67%
6.043	0.318	1.924	0.40%
6.527	0.318	2.074	0.22%
7.008	0.317	2.224	0.11%
7.493	0.317	2.376	0.03%
8.051	0.317	2.551	-0.05%
8.509	0.317	2.694	-0.13%
8.990	0.317	2.846	-0.15%
9.482	0.317	3.001	-0.17%
10.028	0.317	3.175	-0.13%
10.554	0.316	3.330	-0.47%
11.063	0.316	3.501	-0.18%
11.558	0.317	3.659	-0.15%
12.023	0.317	3.806	-0.16%
12.632	0.317	4.000	-0.12%
13.025	0.317	4.127	-0.05%
13.580	0.317	4.305	-0.01%
14.053	0.317	4.458	0.05%
14.524	0.317	4.608	0.06%
15.124	0.318	4.803	0.16%
15.518	0.318	4.928	0.18%
16.014	0.318	5.091	0.27%
16.535	0.318	5.258	0.30%
17.083	0.318	5.434	0.34%
Avg	0.317		



Summary

- Solid state ballast tube emulator with resistive characteristic verified
- Synchronous Rectifier was just for fun, not really needed
- Meets minimum voltage, regulation and power dissipation requirements
- Close to original glass envelop size
- Terminations and mechanical – user’s choice
- Complexity – is it worth it ? your judgement

Resources:

- Schematic, PCB CAM files and project photos available on www.archive.org, “Ballast tube emulator” files
- US Patent US3732507 (A) — 1973-05-08, AC POWER SUPPLY HAVING COMPUTER CONTROLLED FREQUENCY AND PHASE AND AMPLITUDE , CHRISTIANSEN R; BALASUBRAMANIAM D, Fig.5 use of amplitude regulator using CdS photocell